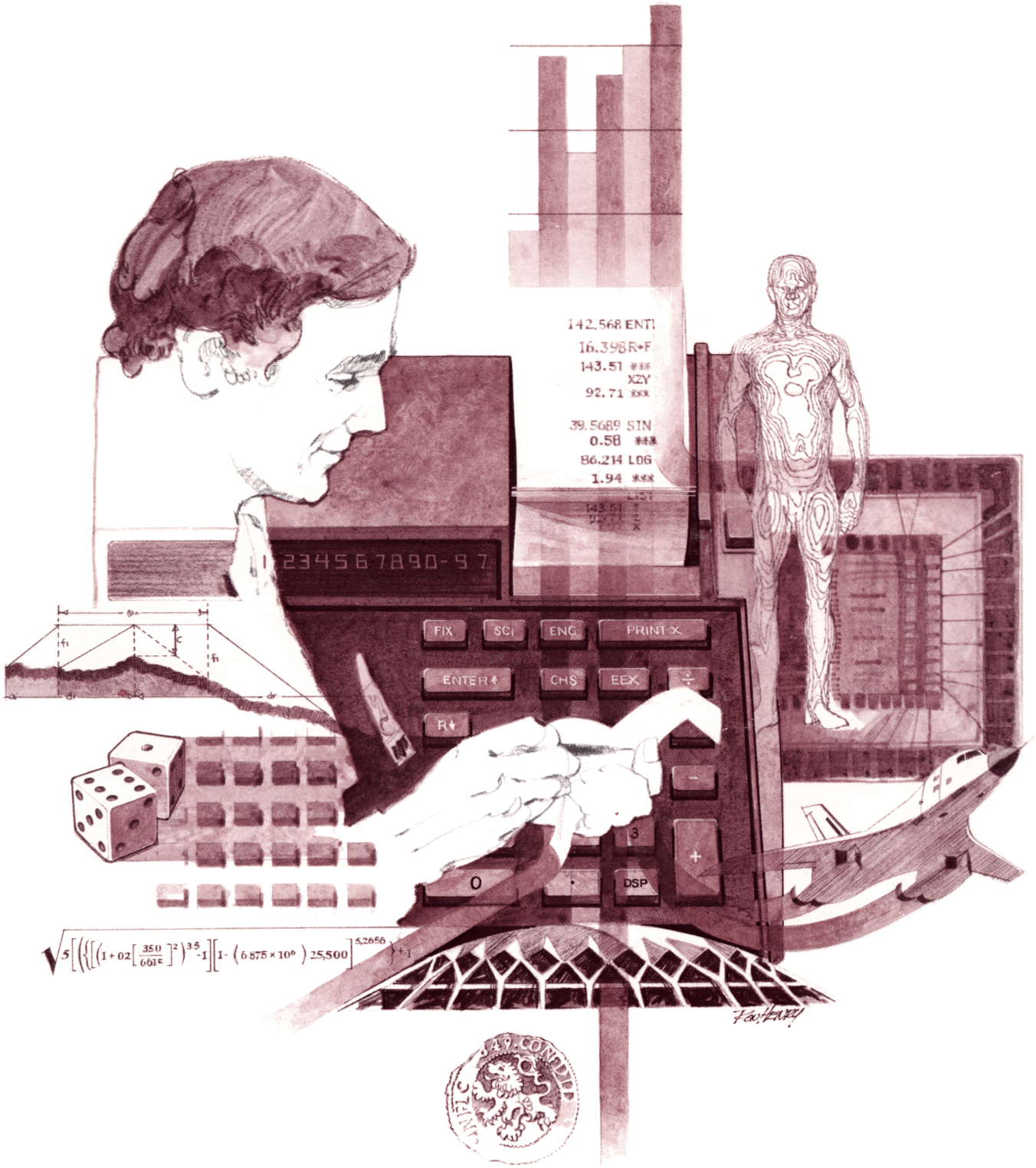
HEWLETT-PACKARD

# HP-67/HP-97

Users' Library Solutions

## Butterworth and Chebyshev Filters



## INTRODUCTION

In an effort to provide continued value to it's customers, Hewlett-Packard is introducing a unique service for the HP fully programmable calculator user. This service is designed to save you time and programming effort. As users are aware, Programmable Calculators are capable of delivering tremendous problem solving potential in terms of power and flexibility, but the real genie in the bottle is program solutions. HP's introduction of the first handheld programmable calculator in 1974 immediately led to a request for program **solutions** — hence the beginning of the HP-65 Users' Library. In order to save HP calculator customers time, users wrote their own programs and sent them to the Library for the benefit of other program users. In a short period of time over 5,000 programs were accepted and made available. This overwhelming response indicated the value of the program library and a Users' Library was then established for the HP-67/97 users.

To extend the value of the Users' Library, Hewlett-Packard is introducing a unique service—a service designed to save you time and money. The Users' Library has collected the best programs in the most popular categories from the HP-67/97 and HP-65 Libraries. These programs have been packaged into a series of low-cost books, resulting in substantial savings for our valued HP-67/97 users.

We feel this new software service will extend the capabilities of our programmable calculators and provide a great benefit to our HP-67/97 users.

## A WORD ABOUT PROGRAM USAGE

Each program contained herein is reproduced on the standard forms used by the Users' Library. Magnetic cards are not included. The Program Description I page gives a basic description of the program. The Program Description II page provides a sample problem and the keystrokes used to solve it. The User Instructions page contains a description of the keystrokes used to solve problems in general and the options which are available to the user. The Program Listing I and Program Listing II pages list the program steps necessary to operate the calculator. The comments, listed next to the steps, describe the reason for a step or group of steps. Other pertinent information about data register contents, uses of labels and flags and the initial calculator status mode is also found on these pages. Following the directions in your HP-67 or HP-97 **Owners' Handbook and Programming Guide,** "Loading a Program" (page 134, HP-67; page 119, HP-97), key in the program from the Program Listing I and Program Listing II pages. A number at the top of the Program Listing indicates on which calculator the program was written (HP-67 or HP-97). If the calculator indicated differs from the calculator you will be using, consult Appendix E of your **Owner's Handbook** for the corresponding keycodes and keystrokes converting HP-67 to HP-97 keycodes and vice versa. No program conversion is necessary. The HP-67 and HP-97 are totally compatible, but some differences do occur in the keycodes used to represent some of the functions.

A program loaded into the HP-67 or HP-97 is not permanent—once the calculator is turned off, the program will not be retained. You can, however, permanently save any program by recording it on a blank magnetic card, several of which were provided in the Standard Pac that was shipped with your calculator. Consult your **Owner's Handbook** for full instructions. A few points to remember:

> The Set Status section indicates the status of flags, angular mode, and display setting. After keying in your program, review the status section and set the conditions as indicated before using or permanently recording the program.
>
> REMEMBER! To save the program permanently, **clip** the corners of the magnetic card once you have recorded the program. This simple step will protect the magnetic card and keep the program from being inadvertently erased.

As a part of HP's continuing effort to provide value to our customers, we hope you will enjoy our newest concept.

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# Program Description I

**Program Title** Butterworth Active Filter Design, Low Pass

**Contributor's Name** Hewlett-Packard

**Address** 1000 N.E. Circle Blvd.

**City** Corvallis **State** Oregon **Zip Code** 97330

**Program Description, Equations, Variables** Refer to the figure on the following page. From attenuation requirements of Amax in the passband whose edge is at $\omega_L$, and Amin attenuation in the stopband starting at $\omega_H$, the required filter order "n" is found as:

$$n = \frac{\log\left[(10^{0.1Amin}-1)/(10^{0.1Amax}-1)\right]}{2\log\frac{\omega H}{\omega_L}}$$

For a given $\omega_L$ with n determined, attenuation A ($\omega$) is

$$A(\omega) = 10\log\left[1 + \left(\frac{\omega}{\omega_L'}\right)^{2n}\right], \quad \omega_L' = \frac{\omega_L}{\left(10^{\frac{Amax}{10}}-1\right)^{1/2n}}$$

The roots of the transfer function may then be found from:

$$Sn = e^{j\frac{(n+2k-1)\pi}{2n}} \quad \text{for n odd}$$

or

$$Sn = e^{j\left[\frac{(k+1)\pi}{2n} + \frac{\pi}{4}\right]} \quad \text{for n even}$$

where k = 1,2,....n

**Operating Limits and Warnings** Attenuation is entered and determined as a positive quantity, in db for all cases. $\omega_L$, $\omega_H$, $\omega$ are in radians/second.

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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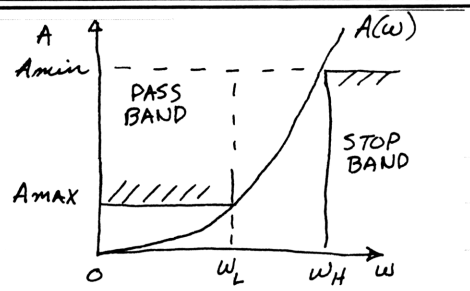
# Program Description II

**Sketch(es)**




**Sample Problem(s)**

1) Given requirements of $A_{MAX}$ = 5 dB at 1 k rad/sec $A_{MIN}$ = 45 dB at 4.85 k rad/sec, determine the order of a Butterworth Filter to meet the requirements.

2) For frequencies of 0.7, 0.8, 0.9, 1, 1.1, 1.2, 4.85 k rad/sec determine the attenuation in dB.

3) Find the poles of the transfer function

$$\frac{(\omega_L')^{2n}}{(s+\alpha_1 \pm j\omega_1)(s+\alpha_2 \pm j\omega_2)\ \ldots\ldots (s+\alpha_n \pm j\omega_n)}$$

NOTE: For $s = j\omega = 0$, $\omega_L'(\alpha_1+j\omega_1)\omega_L'(\alpha_1-j\omega_1)\ldots = (\omega_L')^{2n}$

**Solution(s)**

1) n = 4

2)

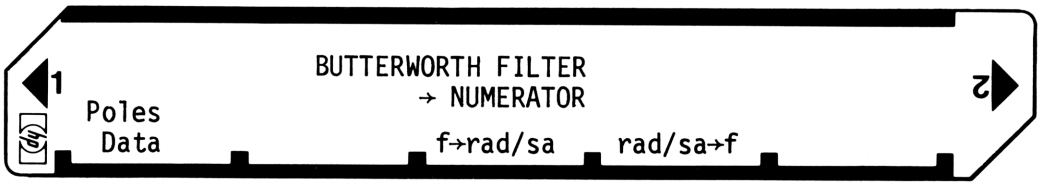
| ω,rad/sec | A,dB |
|---|---|
| 700 | 0.5102 |
| 800 | 1.3442 |
| 900 | 2.8573 |
| 1000 | 5.0000 |
| 1100 | 7.5090 |
| 1200 | 10.1273 |
| 4850 | 58.2085 |

3) -347.52+j838.98
-838.98+j347.52
-838.98+j347.52
-347.52+j838.98

**Reference(s)**

This program is a translation of the HP-65 Users' Library program #04766A submitted by Harvey C. Morehouse.

# User Instructions




| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1. | Load program | | | | |
| | | | | | |
| 2. | Enter data | Amax(db) | ↑ | | |
| | A is positive | $\omega_L$ (rad/sec) | ↑ | | |
| | | Amin(db) | ↑ | | |
| | | $\omega_H$ | A | | n |
| | | | | | |
| 3. | To see $A(\omega)$ | $\omega_1$ (rad/sec) | B | | $A(\omega_1)$ db |
| | | | | | |
| 4. | Repeat 3 as required | | | | |
| | | | | | |
| 5. | To calculate poles of transfer function | | f | A | $\alpha_1$ |
| | | | | | |
| 6. | To see $\omega_1$, | | | x→y | $\omega_1$ |
| | | | | | |
| 7. | To see next poles | | R/S | | $\alpha_i$ |
| | | | x⇄y | | $\omega_i$ |
| | | | | | |
| 8. | Repeat step 7 until "Error" appears, then | | | | |
| | press any key | | | | |
| | | | | | |
| 9. | To see transfer function numerator | | f | C | $(\omega_L')^{2n}$ |

# 97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | |
| 002 | STO4 | 35 04 | |
| 003 | R↓ | -31 | |
| 004 | STO3 | 35 03 | Amax, $\omega_L$, Amin, $\omega_H$ |
| 005 | R↓ | -31 | |
| 006 | STO2 | 35 02 | used to calculate |
| 007 | R↓ | -31 | |
| 008 | STO1 | 35 01 | n, $\omega_L'$ |
| 009 | RCL3 | 36 03 | |
| 010 | GSBE | 23 15 | |
| 011 | RCL1 | 36 01 | |
| 012 | GSBE | 23 15 | |
| 013 | ÷ | -24 | |
| 014 | LOG | 16 32 | |
| 015 | RCL4 | 36 04 | |
| 016 | RCL2 | 36 02 | |
| 017 | ÷ | -24 | |
| 018 | LOG | 16 32 | |
| 019 | ÷ | -24 | |
| 020 | 2 | 02 | |
| 021 | ÷ | -24 | |
| 022 | . | -62 | |
| 023 | 9 | 09 | |
| 024 | 9 | 09 | |
| 025 | + | -55 | |
| 026 | INT | 16 34 | |
| 027 | STO5 | 35 05 | |
| 028 | RCL2 | 36 02 | |
| 029 | RCL1 | 36 01 | |
| 030 | GSBE | 23 15 | $\omega_L'$ calculated - |
| 031 | RCL5 | 36 05 | Note that if Amax = |
| 032 | 2 | 02 | |
| 033 | × | -35 | 3 db, $\omega_L' = \omega_L$ |
| 034 | 1/X | 52 | |
| 035 | $Y^x$ | 31 | |
| 036 | ÷ | -24 | |
| 037 | STO6 | 35 06 | |
| 038 | RCL5 | 36 05 | |
| 039 | RTN | 24 | |
| 040 | *LBLB | 21 12 | n displayed |
| 041 | ENT↑ | -21 | A(ω) plot routine |
| 042 | ENT↑ | -21 | |
| 043 | RCL6 | 36 06 | |
| 044 | ÷ | -24 | |
| 045 | RCL5 | 36 05 | |
| 046 | 2 | 02 | |
| 047 | × | -35 | |
| 048 | $Y^x$ | 31 | |
| 049 | 1 | 01 | |
| 050 | + | -55 | |
| 051 | LOG | 16 32 | |
| 052 | 1 | 01 | |
| 053 | 0 | 00 | |
| 054 | × | -35 | |
| 055 | RTN | 24 | |
| 056 | *LBLE | 21 15 | |
| 057 | 1 | 01 | |
| 058 | 0 | 00 | |
| 059 | ÷ | -24 | |
| 060 | $10^x$ | 16 33 | |
| 061 | 1 | 01 | |
| 062 | - | -45 | |
| 063 | RTN | 24 | |
| 064 | *LBLC | 21 13 | |
| 065 | Pi | 16-24 | |
| 066 | 2 | 02 | |
| 067 | × | -35 | |
| 068 | × | -35 | |
| 069 | RTN | 24 | |
| 070 | *LBLD | 21 14 | |
| 071 | Pi | 16-24 | |
| 072 | ÷ | -24 | |
| 073 | 2 | 02 | |
| 074 | ÷ | -24 | A (ω) displayed |
| 075 | RTN | 24 | |
| 076 | *LBLa | 21 16 11 | |
| 077 | 1 | 01 | |
| 078 | STO7 | 35 07 | |
| 079 | RCL5 | 36 05 | |
| 080 | 2 | 02 | |
| 081 | ÷ | -24 | |
| 082 | FRC | 16 44 | |
| 083 | 0 | 00 | If n is even then |
| 084 | X=Y? | 16-33 | |
| 085 | GTOe | 22 16 15 | go to e n odd |
| 086 | *LBLb | 21 16 12 | |
| 087 | RCL5 | 36 05 | |
| 088 | 1 | 01 | |
| 089 | - | -45 | |
| 090 | RCL7 | 36 07 | |
| 091 | GSBd | 23 16 14 | Display pole |
| 092 | R/S | 51 | |
| 093 | RCL5 | 36 05 | |
| 094 | RCL7 | 36 07 | |
| 095 | 1 | 01 | |
| 096 | + | -55 | |
| 097 | STO7 | 35 07 | If done THEN |
| 098 | X≤Y? | 16-35 | |
| 099 | GTOb | 22 16 12 | "ERROR" else G to b |
| 100 | 0 | 00 | n even |
| 101 | ÷ | -24 | |
| 102 | *LBLe | 21 16 15 | |
| 103 | RCL5 | 36 05 | |
| 104 | 1 | 01 | |
| 105 | + | -55 | |
| 106 | RCL7 | 36 07 | |
| 107 | 1 | 01 | |
| 108 | - | -45 | |
| 109 | GSBd | 23 16 14 | Display pole |
| 110 | R/S | 51 | |
| 111 | RCL5 | 36 05 | |
| 112 | RCL7 | 36 07 | |

REGISTERS

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| | Amax (db) | $\omega_L$ (rad/sec) | Amin (db) | $\omega_H$ )rad/sec) | n | $\omega_L'$ (rad/sec) | ω (rad/sec) | | |
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| | | | | | |

# 97 Program Listing II



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 113 | 1 | 01 | |
| 114 | + | -55 | |
| 115 | STO7 | 35 07 | |
| 116 | X≤Y? | 16-35 | |
| 117 | GTOe | 22 16 15 | |
| 118 | 0 | 00 | |
| 119 | ÷ | -24 | |
| 120 | *LBLc | 21 16 13 | |
| 121 | RCL6 | 36 06 | |
| 122 | RCL5 | 36 05 | |
| 123 | 2 | 02 | |
| 124 | x | -35 | |
| 125 | *LBLd | 21 16 14 | |
| 126 | 2 | 02 | |
| 127 | x | -35 | |
| 128 | + | -55 | |
| 129 | Pi | 16-24 | |
| 130 | x | -35 | |
| 131 | RCL5 | 36 05 | |
| 132 | ÷ | -24 | |
| 133 | 2 | 02 | |
| 134 | ÷ | -24 | |
| 135 | RCL6 | 36 06 | |
| 136 | →R | 44 | |
| 137 | RTN | 24 | |
| 138 | $Y^x$ | 31 | |
| 139 | R/S | 51 | |
| 140 | | | |
| 150 | | | |
| 160 | | | |
| 170 | | | |
| 180 | | | |
| 190 | | | |
| 200 | | | |
| 210 | | | |
| 220 | | | |

| LABELS | | | | | FLAGS |
|---|---|---|---|---|---|
| A | B | C | D | E | 0 |
| a | b | c | d | e | 1 |
| 0 | 1 | 2 | 3 | 4 | 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 2 | |

# Program Description I

**Program Title** Butterworth and Chebyshev Filter Response

**Contributor's Name** Hewlett-Packard
**Address** 1000 N.E. Circle Blvd.
**City** Corvallis **State** Oregon **Zip Code** 97330

**Program Description, Equations, Variables** The Butterworth Filter Response is:

Attenuation = 10 LOG $[1+(Z)^{2n}]$

Where $Z = \frac{f_x}{f_{HCO}}$ for low pass

$Z = \frac{f_x}{f_{LCO}}$ for high pass

$Z = \frac{2f_x-(f_{HCO}+f_{LCO})}{f_{HCO}-f_{LCO}}$ for band pass

$n$ = Number of poles

$f_{HCO}$ = High frequency cutoff
$f_{LCO}$ = Low frequency cutoff
} - 3DB points

$f_x$ = Frequency at which attenuation is to be calculated

**Operating Limits and Warnings**

This program has been verified only with respect to the numerical example given in *Program Description II.* User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

**Program Title** Butterworth and Chebyshev Filter Response

**Contributor's Name** Hewlett-Packard
**Address** 1000 N.E. Circle Blvd.
**City** Corvallis **State** Oregon **Zip Code** 97330

**Program Description, Equations, Variables**

The Filter Response Equations are:

Inside Pass Band

$$\text{Atten} = 10 \text{ LOG } [1 + (10^{\frac{RIP}{10}} - 1) \cos^2(n \cos^{-1} Z)]$$

Outside Pass Band

$$\text{Atten} = 10 \text{ LOG } [1 + (10^{\frac{RIP}{10}} - 1) \cosh^2(n \cosh^{-1} Z)]$$

Where $= Z = \frac{f_x}{f_{CO}}$ for low pass filter

$Z = \frac{f_{CO}}{f_x}$ for high pass filter

$n$ = Number of poles

RIP = Passband ripple

$f_{CO}$ = Cutoff frequency

$f_x$ = Any frequency for which the attenuation is desired

**Operating Limits and Warnings**

RIP = 0

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

**Program Title** Butterworth and Chebyshev Filter Response

**Contributor's Name** Hewlett-Packard
**Address** 1000 N.E. Circle Blvd.
**City** Corvallis **State** Oregon **Zip Code** 97330

**Program Description, Equations, Variables** The Band Pass Filter Response is:

Inside Pass Band

$$\text{Attenuation} = 10\ \text{LOG}[1 + (10^{\frac{RIP}{n}} - 1)\ \text{COS}^2\ (n\ \text{COS}^{-1} Z)]$$

Outside Pass Band

$$\text{Attenuation} = 10\ \text{LOG}\ [\ 1 + (10^{\frac{RIP}{10}} - 1)\ \text{COSH}^2\ (n\ \text{COSH}^{-1} Z)]$$

$$\text{Where } Z = \frac{2\ f_x - (f_{HCO} + f_{LCO})}{f_{HCO} - f_{LCO}}$$

$f_x$ = Frequency at which attenuation is to be calculated

$f_{HCO}$ = High frequency cutoff

$f_{LCO}$ = Low frequency cutoff

n = Number of poles

RIP = Pass band ripple

**Operating Limits and Warnings**

RIP = 0

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# Program Description II

**Sketch(es)**

**Sample Problem(s)**

Given a Butterworth Band Pass Filter

Number of poles = 5

$f_{LCO}$ = 10

$f_{HCO}$ = 14

Find Attenuation at:

| | |
|---|---|
| 9 MHZ | 10 MHZ |
| 11 MHZ | 12 MHZ |
| 13 MHZ | 14 MHZ |
| 15 MHZ | |

**Solution(s)**

| | |
|---|---|
| 5[A] 10[B] 14[f] [B] 9[D] | Atten = -17.68 dB |
| 10[D] | Atten = -3.01 dB |
| 11[D] | Atten = -0.00 dB |
| 12[D] | Atten = 0.00 dB |
| 13[D] | Atten = -0.00 dB |
| 14[D] | Atten = -3.01 dB |
| 15[D] | Atten = -17.68 dB |

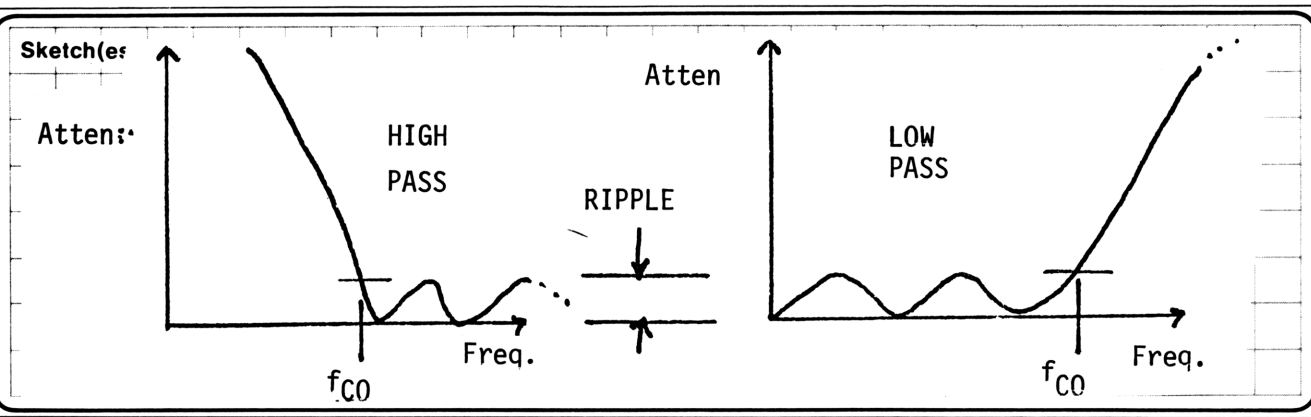
**Reference(s)**

Reference Data for Radio Engineers, fifth edition. pgs. 8-1 thru 8-23, How-rd W. Sams & Co., 1972.

This program is a combination of User's Library programs 1807A, 1808A and 1809A by Paul Bunnell.

# Program Description II

**Sketch(es)**




**Sample Problem(s)**

Given Ripple = 3 DB
$f_{CO}$ = 10 MHZ
Poles = 5

Determine Low Pass Response for
7 MHZ
8 MHZ
9 MHZ
10 MHZ
11 MHZ
12 MHZ

**Solution(s)**

| | |
|---|---|
| 5[A] 3[f] [A] 10 [f] [B] 7 [f] [C] | Atten = -1.61 dB |
| 8 [f] [C] | Atten = -2.99 dB |
| 9 [f] [C] | Atten = -1.45 dB |
| 10 [f] [C] | Atten = -3.00 dB |
| 11 [f] [C] | Atten = -13.52 dB |
| 12 [f] [C] | Atten = -21.04 dB |

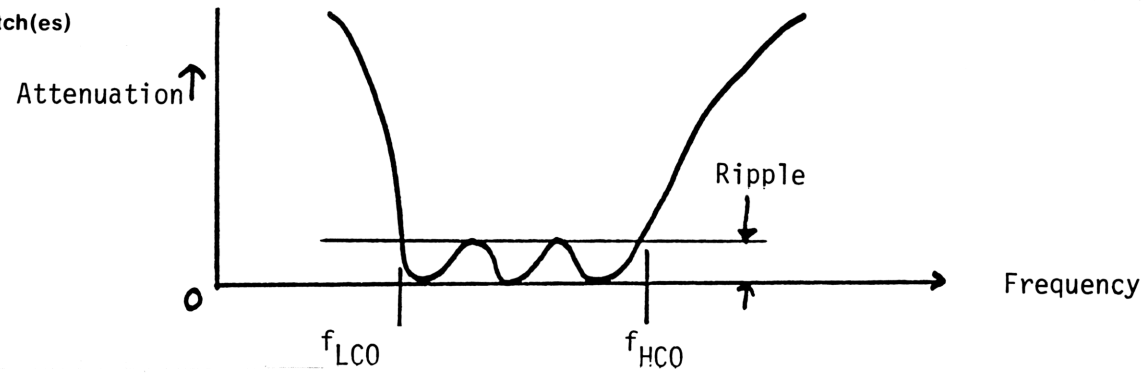
**Reference(s)**

Reference Data for Radio Engineers, Fifth Edition, Pgs. 8-1 thru 8-28, Howard W. Sams & Co., 1972.

This program is a combination of Users' Library programs 1807A, 1808A and 1809A by Paul Bunnell.

# Program Description II

**Sketch(es)**




**Sample Problem(s)**

Given Ripple = 3 DB
$f_{LCO}$ = 10 MHZ
$f_{HCO}$ = 14 MHZ
Poles = 5

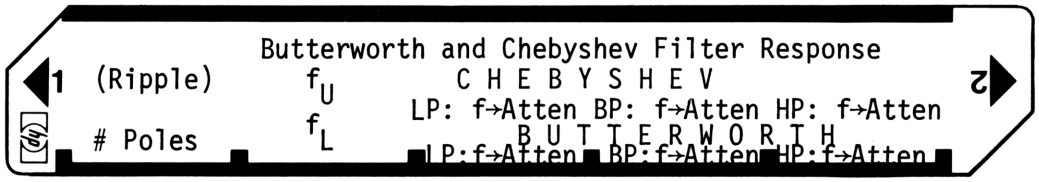
Find Band Pass Chebyshev Response at
9 MHZ
10 MHZ
11 MHZ
12 MHZ
13 MHZ
14 MHZ
15 MHZ

**Solution(s)**

| | |
|---|---|
| 5 [A] 3 [f] [A] 10 [B] 14 [f] [B] 9[f] [D] | Atten =-35.76 dB |
| 10[f] [D] | Atten = -3.00 dB |
| 11[f] [D] | Atten = -0.96 dB |
| 12[f] [D] | Atten = 0.00 dB |
| 13[f] [D] | Atten = -0.96 dB |
| 14[f] [D] | Atten = -3.00 dB |
| 15[f] [D] | Atten =-35.76 dB |

**Reference(s)**

# User Instructions




| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1. | Load program | | | | |
| | | | | | |
| 2. | Enter filter description | | | | |
| | Number of poles | n | A | | |
| | Pass band ripple (for chebyshev filters) | Ripple DB | f | A | |
| | Lower cutoff frequency (BP and HP) | $f_L$,* | B | | |
| | Upper cutoff frequency (LP and BP) | $f_U$,* | f | B | |
| | | | | | |
| 3. | Key in frequency of interest and compute | | | | |
| | response of desired filter: | | | | |
| | Butterworth Low Pass | f,* | C | | Atten dB |
| | Butterworth Band Pass | f,* | D | | Atten dB |
| | Butterworth High Pass | f,* | E | | Atten dB |
| | Chebyshev Low Pass | f,* | f | C | Atten dB |
| | Chebyshev Band Pass | f,* | f | D | Atten dB |
| | Chebyshev High Pass | f,* | f | E | Atten dB |
| | | | | | |
| 4. | For a new frequency, repeat any (or all) | | | | |
| | line of step 3 as desired. | | | | |
| | | | | | |
| 5. | For new specifications, repeat desired lines | | | | |
| | of step 2. | | | | |
| | | | | | |
| | | | | | |
| * | Use consistant units (Hz.KHz,MHz) | | | | |

# 97 Program Listing I



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | |
| 002 | STO4 | 35 04 | # Poles |
| 003 | RTN | 24 | |
| 004 | *LBLB | 21 12 | |
| 005 | STO2 | 35 02 | Lower cutoff freq. |
| 006 | RTN | 24 | |
| 007 | *LBLb | 21 16 12 | |
| 008 | STO3 | 35 03 | Upper cutoff freq. |
| 009 | RTN | 24 | |
| 010 | *LBLa | 21 16 11 | |
| 011 | STO1 | 35 01 | Frequency |
| 012 | RTN | 24 | |
| 013 | *LBLE | 21 15 | |
| 014 | SF0 | 16 21 00 | High Pass |
| 015 | GTO0 | 22 00 | |
| 016 | *LBLD | 21 14 | |
| 017 | SF0 | 16 21 00 | Band Pass |
| 018 | *LBLC | 21 13 | |
| 019 | SF1 | 16 21 01 | Low Pass |
| 020 | *LBL0 | 21 00 | |
| 021 | STO0 | 35 00 | |
| 022 | F0? | 16 23 00 | |
| 023 | F1? | 16 23 01 | |
| 024 | GTO1 | 22 01 | |
| 025 | RCL2 | 36 02 | |
| 026 | X⇄Y | -41 | |
| 027 | *LBL3 | 21 03 | |
| 028 | ÷ | -24 | |
| 029 | *LBL2 | 21 02 | |
| 030 | RCL4 | 36 04 | |
| 031 | 2 | 02 | |
| 032 | × | -35 | |
| 033 | $Y^x$ | 31 | |
| 034 | 1 | 01 | |
| 035 | + | -55 | |
| 036 | LOG | 16 32 | |
| 037 | 1 | 01 | |
| 038 | 0 | 00 | |
| 039 | × | -35 | |
| 040 | CHS | -22 | |
| 041 | CF0 | 16 22 00 | |
| 042 | CF1 | 16 22 01 | |
| 043 | RTN | 24 | |
| 044 | *LBL1 | 21 01 | |
| 045 | RCL3 | 36 03 | |
| 046 | F0? | 16 23 00 | |
| 047 | GTO0 | 22 00 | |
| 048 | GTO3 | 22 03 | |
| 049 | *LBL0 | 21 00 | |
| 050 | RCL2 | 36 02 | |
| 051 | + | -55 | |
| 052 | 2 | 02 | |
| 053 | ÷ | -24 | |
| 054 | - | -45 | |
| 055 | RCL3 | 36 03 | |
| 056 | RCL2 | 36 02 | |
| 057 | - | -45 | |
| 058 | ÷ | -24 | |
| 059 | ABS | 16 31 | |
| 060 | 2 | 02 | |
| 061 | × | -35 | |
| 062 | GTO2 | 22 02 | |
| 063 | *LBLe | 21 16 15 | High Pass |
| 064 | SF2 | 16 21 02 | |
| 065 | *LBLc | 21 16 13 | Low Pass |
| 066 | RCL3 | 36 03 | |
| 067 | F2? | 16 23 02 | C |
| 068 | GSB0 | 23 00 | |
| 069 | ÷ | -24 | H |
| 070 | F2? | 16 23 02 | |
| 071 | 1/X | 52 | E |
| 072 | STO5 | 35 05 | |
| 073 | 1 | 01 | B |
| 074 | X>Y? | 16-34 | |
| 075 | GTO9 | 22 09 | Y |
| 076 | RCL5 | 36 05 | |
| 077 | ENT↑ | -21 | S |
| 078 | × | -35 | |
| 079 | 1 | 01 | H |
| 080 | - | -45 | |
| 081 | √X | 54 | E |
| 082 | RCL5 | 36 05 | |
| 083 | + | -55 | V |
| 084 | LN | 32 | |
| 085 | RCL4 | 36 04 | |
| 086 | × | -35 | |
| 087 | $e^x$ | 33 | |
| 088 | LSTX | 16-63 | |
| 089 | CHS | -22 | |
| 090 | $e^x$ | 33 | |
| 091 | + | -55 | |
| 092 | 2 | 02 | |
| 093 | ÷ | -24 | |
| 094 | *LBL8 | 21 08 | |
| 095 | ENT↑ | -21 | |
| 096 | × | -35 | |
| 097 | RCL1 | 36 01 | |
| 098 | 1 | 01 | |
| 099 | 0 | 00 | |
| 100 | ÷ | -24 | |
| 101 | LSTX | 16-63 | |
| 102 | X⇄Y | -41 | |
| 103 | $Y^x$ | 31 | |
| 104 | 1 | 01 | |
| 105 | - | -45 | |
| 106 | × | -35 | |
| 107 | 1 | 01 | |
| 108 | + | -55 | |
| 109 | LOG | 16 32 | |
| 110 | 1 | 01 | |
| 111 | 0 | 00 | |
| 112 | × | -35 | |

REGISTERS

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| f | Ripple | $f_L$ | $f_U$ | Poles | | | | | |
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| | | | | | | | | | |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| | | | | | |

# 97 Program Listing II

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 113 | CF1 | 16 22 01 | |
| 114 | CHS | -22 | |
| 115 | RTN | 24 | |
| 116 | *LBL0 | 21 00 | |
| 117 | CLX | -51 | |
| 118 | RCL2 | 36 02 | |
| 119 | SF2 | 16 21 02 | |
| 120 | RTN | 24 | |
| 121 | *LBL9 | 21 09 | |
| 122 | RCL5 | 36 05 | |
| 123 | COS⁻¹ | 16 42 | |
| 124 | RCL4 | 36 04 | |
| 125 | × | -35 | |
| 126 | COS | 42 | |
| 127 | GTO8 | 22 08 | |
| 128 | *LBLd | 21 16 14 | Band Pass |
| 129 | RCL2 | 36 02 | |
| 130 | RCL3 | 36 03 | |
| 131 | + | -55 | C |
| 132 | 2 | 02 | |
| 133 | ÷ | -24 | H |
| 134 | - | -45 | |
| 135 | RCL3 | 36 03 | E |
| 136 | RCL2 | 36 02 | |
| 137 | - | -45 | B |
| 138 | ÷ | -24 | |
| 139 | ABS | 16 31 | Y |
| 140 | 2 | 02 | |
| 141 | × | -35 | |
| 142 | STO5 | 35 05 | S |
| 143 | 1 | 01 | |
| 144 | X>Y? | 16-34 | H |
| 145 | GTO7 | 22 07 | |
| 146 | RCL5 | 36 05 | E |
| 147 | ENT↑ | -21 | |
| 148 | × | -35 | V |
| 149 | 1 | 01 | |
| 150 | - | -45 | |
| 151 | √X | 54 | |
| 152 | RCL5 | 36 05 | |
| 153 | + | -55 | |
| 154 | LN | 32 | |
| 155 | RCL4 | 36 04 | |
| 156 | × | -35 | |
| 157 | $e^x$ | 33 | |
| 158 | LSTX | 16-63 | |
| 159 | CHS | -22 | |
| 160 | $e^x$ | 33 | |
| 161 | + | -55 | |
| 162 | 2 | 02 | |
| 163 | ÷ | -24 | |
| 164 | *LBL6 | 21 06 | |
| 165 | ENT↑ | -21 | |
| 166 | × | -35 | |
| 167 | RCL1 | 36 01 | |
| 168 | 1 | 01 | |
| 169 | 0 | 00 | |
| 170 | ÷ | -24 | |
| 171 | LSTX | 16-63 | |
| 172 | X⇄Y | -41 | |
| 173 | $Y^x$ | 31 | |
| 174 | 1 | 01 | |
| 175 | - | -45 | |
| 176 | × | -35 | |
| 177 | 1 | 01 | |
| 178 | + | -55 | |
| 179 | LOG | 16 32 | |
| 180 | 1 | 01 | |
| 181 | 0 | 00 | |
| 182 | × | -35 | |
| 183 | CHS | -22 | |
| 184 | RTN | 24 | |
| 185 | *LBL7 | 21 07 | |
| 186 | RCL5 | 36 05 | |
| 187 | COS⁻¹ | 16 42 | |
| 188 | RCL4 | 36 04 | |
| 189 | × | -35 | |
| 190 | COS | 42 | |
| 191 | GTO6 | 22 06 | |

| LABELS | | | | | FLAGS | SET STATUS |
|---|---|---|---|---|---|---|
| A # Poles | B $f_L$ | C LP: f → dB | D BP: f → dB | E HP: f → dB | 0 | FLAGS / TRIG / DISP |
| a (Ripple) | b $f_U$ | c LP: f → dB | d BP: f → dB | e HP: f → dB | 1 | |
| 0 | 1 | 2 | 3 | 4 | 2 | |
| 5 | 6 | 7 | 8 | 9 | 3 | |

| FLAGS | ON | OFF |
|---|---|---|
| 0 | ☐ | ☒ |
| 1 | ☐ | ☒ |
| 2 | ☐ | ☒ |
| 3 | ☐ | ☒ |

| TRIG | |
|---|---|
| DEG | ☒ |
| GRAD | ☐ |
| RAD | ☐ |

| DISP | |
|---|---|
| FIX | ☒ |
| SCI | ☐ |
| ENG | ☐ |
| n | 2 |

# Program Description I

**Program Title** Butterworth Filter Group Delay

**Contributor's Name** Hewlett-Packard
**Address** 1000 N.E. Circle Blvd.
**City** Corvallis **State** Oregon **Zip Code** 97330

**Program Description, Equations, Variables**

Group Delay is Given by

$$\tau_g = \frac{1}{2\pi(f_{MAX}-f_{MIN})}\left[1 + \frac{f_{MAX}\, f_{MIN}}{f^2}\right] \sum_{k=1}^{n} \frac{|\sigma_k|}{\sigma_k^2 + (\Omega-\omega_k)^2}$$

Where

$\sigma_k = \cos\theta_k$

$\omega_k = \sin\theta_k$

$\theta_k = \left(\frac{2k+n-1}{n}\right) 90$

$$\Omega = \left|\frac{1}{f_{MAX}-f_{MIN}}\left[f - \frac{f_{MAX}\, f_{MIN}}{f}\right]\right|$$

$n$ = Number of poles

$f_{MAX}$ = Upper -3dB frequency

$f_{MIN}$ = Lower -3dB frequency

**Operating Limits and Warnings**

Program is not valid when f = 0.

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

**Program Title** Chebyshev Filter Group Delay

**Contributor's Name** Hewlett-Packard
**Address** 1000 N.E. Circle Blvd.
**City** Corvallis **State** Oregon **Zip Code** 97330

**Program Description, Equations, Variables**

The group delay of a Chebyshev filter at any frequency, f, is given by

$$\tau_g = \frac{1}{2\pi(f_{MAX}-f_{MIN})}\left[1 + \frac{f_{MAX}\ f_{MIN}}{f^2}\right] \sum_{k=1}^{n} \frac{|\sigma_k|}{\sigma_k^2+(\Omega-\omega_k)^2}$$

Where:

$$\sigma_k = \sinh\left[\frac{1}{n}\sinh^{-1} 1/\varepsilon\right] \sin\theta_k$$

$$\omega_k = \cosh\left[\frac{1}{n}\sinh^{-1} 1/\varepsilon\right] \cos\theta_k$$

$$\theta_k = \left(\frac{2k-1}{n}\right) 90$$

$$\Omega = \left|\frac{1}{f_{MAX}-f_{MIN}}\left[f - \frac{f_{MAX}\ f_{MIN}}{f}\right]\right|$$

$$\varepsilon = \sqrt{\mathrm{LOG}^{-1}\frac{A_{MAX}}{10} - 1}$$

n = Number of poles

$A_{MAX}$ = Maximum ripple

$f_{MIN}$ = Lower - $A_{MAX}$ dB frequency

$f_{MAX}$ = Upper - $A_{MAX}$ dB frequency

**Operating Limits and Warnings**

The program is not valid for f = 0

This program has been verified only with respect to the numerical example given in *Program Description II.* User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description II

**Sketch(es)**

**Sample Problem(s)**

1. Calculate the group delay at 90 MHz of a low pass Butterworth Filter with a 100 MHz cutoff frequency when n = 4.

2. Calculate the group delay at 110 MHz of a high pass Butterworth Filter with a 100 MHz cutoff frequency when n = 7.

3. Calculate the group delay at 450 MHz of a band pass Butterworth filter with a lower -3 dB frequency of 400 MHz and a upper -3 dB frequency of 500 MHz when n = 5.

**Solution(s)**

1. $\tau_g = 6.22 \times 10^{-9}$ sec.

2. $\tau_g = 10.1 \times 10^{-9}$ sec.

3. $\tau_g = 10.2 \times 10^{-9}$ sec.

**Reference(s)** This program is a combination of HP-65 User's Library programs 04774A and 4906A by William J. Robertson.

# Program Description II

**Sketch(es)**

**Sample Problem(s)**

a) Find the group delay of a 4 pole band pass Chebyshev filter at 510 MHz when the lower cutoff frequency is 400 MHz, the upper cutoff frequency is 500 MHz and the maximum ripple is 0.5 dB

b) Find the group delay of a 4 pole low pass Chebyshev filter at 95 MHz when the cutoff frequency is 100 MHz and the maximum ripple is 0.1 dB.

c) Find the group delay of a 6 pole high pass Chebyshev filter at 110 MHz when the cutoff frequency is 100 MHz and the maximum ripple is 1 dB.

**Solution(s)**

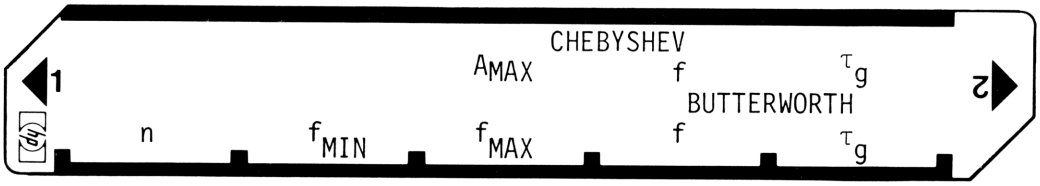
a) $10.8 \times 10^{-9}$ sec.

b) $6.32 \times 10^{-9}$ sec.

c) $12.0 \times 10^{-9}$ sec.

**Reference(s)**

# User Instructions




| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1. | Load program | | | | |
| 2. | Enter (any order) | | | | |
| | n - number of poles | n | A | | |
| | $f_{MIN}$ - lower cutoff frequency* | $f_{MIN}$,Hz | B | | |
| | $f_{MAX}$ - upper cutoff frequency* | $f_{MAX}$,Hz | C | | |
| | FOR BUTTERWORTH FILTERS | | | | |
| 3. | Enter frequency | f,Hz | D | | |
| 4. | Compute time delay | | E | | $\tau_g$, sec. |
| 5. | Repeat steps 3 and 4 for new frequencies | | | | |
| | FOR CHEBYSHEV FILTERS | | | | |
| 3. | Enter maximum pass band ripple | $A_{MIN}$,dB | f | C | |
| 4. | Enter frequency | f,Hz | f | D | |
| 5. | Compute time delay | | f | E | $\tau_g$, sec. |
| 6. | Repeat steps 4 and 5 for new frequencies | | | | |
| 7. | For new case, go to step 2. Be sure to enter zero for $f_{MIN}$ or $10^{50}$ for $f_{MAX}$ if the last case used these variables and the new case does not. | | | | |
| * | For the Butterworth filter, these are 3 dB frequencies; for the Chebyshev filter, they are $A_{MAX}$ dB frequencies. | | | | |

# 97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | |
| 002 | STO1 | 35 01 | |
| 003 | STOI | 35 46 | Store n |
| 004 | 0 | 00 | |
| 005 | STO7 | 35 07 | |
| 006 | RCL1 | 36 01 | |
| 007 | RTN | 24 | |
| 008 | *LBLB | 21 12 | |
| 009 | STO2 | 35 02 | Store $f_{MIN}$ |
| 010 | RTN | 24 | |
| 011 | *LBLC | 21 13 | |
| 012 | STO3 | 35 03 | Store $f_{MAX}$ |
| 013 | RTN | 24 | |
| 014 | *LBLD | 21 14 | |
| 015 | STO4 | 35 04 | Store f |
| 016 | RTN | 24 | |
| 017 | *LBLE | 21 15 | Compute $\tau_g$ for |
| 018 | RCL4 | 36 04 | |
| 019 | RCL3 | 36 03 | Butterworth filer |
| 020 | RCL2 | 36 02 | |
| 021 | × | -35 | |
| 022 | RCL4 | 36 04 | |
| 023 | ÷ | -24 | |
| 024 | - | -45 | |
| 025 | RCL3 | 36 03 | |
| 026 | RCL2 | 36 02 | |
| 027 | - | -45 | |
| 028 | ÷ | -24 | |
| 029 | ABS | 16 31 | |
| 030 | STO6 | 35 06 | |
| 031 | RCLI | 36 46 | |
| 032 | 2 | 02 | |
| 033 | × | -35 | |
| 034 | RCL1 | 36 01 | |
| 035 | + | -55 | |
| 036 | 1 | 01 | |
| 037 | - | -45 | |
| 038 | RCL1 | 36 01 | |
| 039 | ÷ | -24 | |
| 040 | 9 | 09 | |
| 041 | 0 | 00 | |
| 042 | × | -35 | |
| 043 | STO5 | 35 05 | |
| 044 | COS | 42 | |
| 045 | CHS | -22 | |
| 046 | ENT↑ | -21 | |
| 047 | ENT↑ | -21 | |
| 048 | × | -35 | |
| 049 | RCL6 | 36 06 | |
| 050 | RCL5 | 36 05 | |
| 051 | SIN | 41 | |
| 052 | - | -45 | |
| 053 | ENT↑ | -21 | |
| 054 | × | -35 | |
| 055 | + | -55 | |
| 056 | ÷ | -24 | |
| 057 | ST+7 | 35-55 07 | |
| 058 | DSZI | 16 25 46 | |
| 059 | GTOE | 22 15 | |
| 060 | RCL7 | 36 07 | |
| 061 | 2 | 02 | |
| 062 | ÷ | -24 | |
| 063 | Pi | 16-24 | |
| 064 | ÷ | -24 | |
| 065 | RCL3 | 36 03 | |
| 066 | RCL2 | 36 02 | |
| 067 | - | -45 | |
| 068 | ÷ | -24 | |
| 069 | RCL3 | 36 03 | |
| 070 | RCL2 | 36 02 | |
| 071 | × | -35 | |
| 072 | RCL4 | 36 04 | |
| 073 | ENT↑ | -21 | |
| 074 | × | -35 | |
| 075 | + | -55 | |
| 076 | LSTX | 16-63 | |
| 077 | ÷ | -24 | |
| 078 | × | -35 | |
| 079 | STO6 | 35 06 | |
| 080 | RCL1 | 36 01 | |
| 081 | STOI | 35 46 | |
| 082 | 0 | 00 | |
| 083 | STO7 | 35 07 | |
| 084 | RCL6 | 36 06 | |
| 085 | RTN | 24 | |
| 086 | *LBLc | 21 16 13 | |
| 087 | STOC | 35 13 | Store $A_{MAX}$ |
| 088 | RTN | 24 | |
| 089 | *LBLd | 21 16 14 | |
| 090 | GSBD | 23 14 | Store f |
| 091 | RCL2 | 36 02 | |
| 092 | RCL3 | 36 03 | Precompute some |
| 093 | × | -35 | |
| 094 | STOA | 35 11 | constants |
| 095 | RCL2 | 36 02 | |
| 096 | RCL3 | 36 03 | |
| 097 | - | -45 | |
| 098 | STOB | 35 12 | |
| 099 | RCLC | 36 13 | |
| 100 | 1 | 01 | |
| 101 | 0 | 00 | |
| 102 | ÷ | -24 | |
| 103 | 10ˣ | 16 33 | |
| 104 | 1 | 01 | |
| 105 | - | -45 | |
| 106 | √X | 54 | |
| 107 | 1/X | 52 | |
| 108 | STO7 | 35 07 | |
| 109 | ENT↑ | -21 | |
| 110 | × | -35 | |
| 111 | 1 | 01 | |
| 112 | + | -55 | |

**REGISTERS**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| | n | $f_{MIN}$ | $f_{MAX}$ | f | Used | Used | Used | | Used |
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| | | | | | | | | | |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| $f_{MIN}$ $f_{MAX}$ | $f_{MIN}-f_{MAX}$ | $A_{MAX}$ | | | Counter |

# 97 Program Listing II



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 113 | √X | 54 | |
| 114 | RCL7 | 36 07 | |
| 115 | + | -55 | |
| 116 | LN | 32 | |
| 117 | RCL1 | 36 01 | |
| 118 | ÷ | -24 | |
| 119 | STO7 | 35 07 | |
| 120 | $e^x$ | 33 | |
| 121 | STOI | 35 46 | |
| 122 | RCL7 | 36 07 | |
| 123 | CHS | -22 | |
| 124 | $e^x$ | 33 | |
| 125 | STOD | 35 14 | |
| 126 | - | -45 | |
| 127 | 2 | 02 | |
| 128 | ÷ | -24 | |
| 129 | STO6 | 35 06 | |
| 130 | RCLI | 36 46 | |
| 131 | RCLD | 36 14 | |
| 132 | + | -55 | |
| 133 | 2 | 02 | |
| 134 | ÷ | -24 | |
| 135 | STO5 | 35 05 | |
| 136 | 0 | 00 | |
| 137 | STO7 | 35 07 | |
| 138 | RCL1 | 36 01 | |
| 139 | STOI | 35 46 | |
| 140 | RTN | 24 | |
| 141 | *LBLe | 21 16 15 | Compute $\tau_g$ |
| 142 | RCLI | 36 46 | |
| 143 | 2 | 02 | |
| 144 | × | -35 | for Chebyshev |
| 145 | 1 | 01 | filter |
| 146 | - | -45 | |
| 147 | RCL1 | 36 01 | |
| 148 | ÷ | -24 | |
| 149 | 9 | 09 | |
| 150 | 0 | 00 | |
| 151 | × | -35 | |
| 152 | STO9 | 35 09 | |
| 153 | RCL4 | 36 04 | |
| 154 | RCLA | 36 11 | |
| 155 | RCL4 | 36 04 | |
| 156 | ÷ | -24 | |
| 157 | - | -45 | |
| 158 | RCLB | 36 12 | |
| 159 | ÷ | -24 | |
| 160 | ABS | 16 31 | |
| 161 | RCL9 | 36 09 | |
| 162 | ENT↑ | -21 | |
| 163 | COS | 42 | |
| 164 | RCL5 | 36 05 | |
| 165 | × | -35 | |
| 166 | X⇄Y | -41 | |
| 167 | SIN | 41 | |
| 168 | RCL6 | 36 06 | |
| 169 | × | -35 | |
| 170 | CHS | -22 | |
| 171 | ENT↑ | -21 | |
| 172 | × | -35 | |
| 173 | LSTX | 16-63 | |
| 174 | X⇄Y | -41 | |
| 175 | R↑ | 16-31 | |
| 176 | R↑ | 16-31 | |
| 177 | - | -45 | |
| 178 | $X^2$ | 53 | |
| 179 | + | -55 | |
| 180 | ÷ | -24 | |
| 181 | ST+7 | 35-55 07 | |
| 182 | DSZI | 16 25 46 | |
| 183 | GTOe | 22 16 15 | |
| 184 | RCL7 | 36 07 | |
| 185 | 2 | 02 | |
| 186 | ÷ | -24 | |
| 187 | Pi | 16-24 | |
| 188 | ÷ | -24 | |
| 189 | RCLB | 36 12 | |
| 190 | ÷ | -24 | |
| 191 | RCLA | 36 11 | |
| 192 | RCL4 | 36 04 | |
| 193 | ENT↑ | -21 | |
| 194 | × | -35 | |
| 195 | ÷ | -24 | |
| 196 | 1 | 01 | |
| 197 | + | -55 | |
| 198 | × | -35 | |
| 199 | STO9 | 35 09 | |
| 200 | RCL1 | 36 01 | |
| 201 | STOI | 35 46 | |
| 202 | 0 | 00 | |
| 203 | STO7 | 35 07 | |
| 204 | RCL9 | 36 09 | |
| 205 | RTN | 24 | |
| 206 | R/S | 51 | |
| 210 | | | |
| 220 | | | |

| LABELS | | | | | FLAGS |
|---|---|---|---|---|---|
| A n | B $f_{MIN}$ | C $f_{MAX}$ | D f | E $\rightarrow\tau_g$ | 0 |
| a | b | c $A_{MAX}$ | d f | e $\rightarrow\tau_g$ | 1 |
| 0 | 1 | 2 | 3 | 4 | 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 | 2 |

# Program Description I

**Program Title**

BUTTERWORTH AND CHEBYCHEV FILTER ORDER CALCULATIONS

**Contributor's Name** Bruce K. Murdock

**Address** 6875 Sabado Tarde Road

**City** Goleta **State** Calif **Zip Code** 93017

**Program Description, Equations, Variables**

This program solves for the required Butterworth, or Chebychev filter order required to meet given filter passband attenuation and stopband attenuation requirements. Alternatively one may solve for the stopband to passband frequency ratio, $\lambda$, if the filter order, n, is given. A third part of the program will predict the stopband attenuation if n, $\lambda$, and the passband attenuation, $Ap_{dB}$, are given.

This program accomplishes analytically the same solutions that the Kawakami nomographs accomplish graphically. These nomographs are shown in program 00401D, 97-Butterworth and Chebychev Lowpass Normalized Coefficients.

**Operating Limits and Warnings** none

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

The analytic expressions for Butterworth and Chebychev filter characteristics are given at the bottom of the respective nomograph. These equations may be rearranged to allow solving for the filter parameters by analytical means.

In the Butterworth case

$$A_s^2 - 1 = (A_p^2 - 1)\lambda^{2n} \quad \text{where}$$

$A_s$ = minimum stophand attenuation

$A_p$ = maximum passband attenuation

$n$ = filter order

$\lambda$ = stopband to passband frequency ratio

$A_p$ and $A_s$ are ratios > 1 in this equation and are normally expressed in terms of decibels (the convention is to express attenuation as positive decibels) i.e.

$$A_s = 10^{\frac{A_s(dB)}{10}} \; ; \; A_p = 10^{\frac{A_p(dB)}{10}}$$

when these substitutions are made, the Butterworth equation becomes.

$$10^{\frac{A_s(dB)}{10}} - 1 = \left\{ 10^{\frac{A_p(dB)}{10}} - 1 \right\} \lambda^{2n}$$

This equation may be rewritten to solve for either $A_s(dB)$, $\lambda$, or $n$

$$1)\; A_s(dB) = 10 \log_{10} \left\{ \left( 10^{\frac{A_p(dB)}{10}} - 1 \right) \lambda^{2n} + 1 \right\}$$

(positive dB's represent attenuation)

$$2)\; n = \frac{\log\left( 10^{\frac{A_s(dB)}{10}} - 1 \right) - \log\left( 10^{\frac{A_p(dB)}{10}} - 1 \right)}{2 \log \lambda}$$

A program has been written for a programmable calculator to solve for the above variables i.e. to find $A_s(dB)$ given $A_p(dB)$, $n$, and $\lambda$ or $\lambda$ given $A_p(dB)$, $A_s(dB)$, and $n$ or $n$ given $A_p(dB)$, $A_s(dB)$, and $\lambda$.

# Program Description I

The analytic expressions for the Chebychev case may be solved in a similar manner, i.e.

$$A_s^2 - 1 = (A_p^2 - 1)\left\{\cosh(n \cosh^{-1}\lambda)\right\}^2$$

$A_s$ = minimum stopband attenuation

$A_p$ = maximum passband attenuation (maximum ripple)

$n$ = filter order

$\lambda$ = stopband to passband frequency ratio

The convention is to express attenuation as a ratio > 1, or in positive decibels. $A_s$ and $A_p$ may be expressed in their dB equivalents

$$A_s = 10^{\left(\frac{A_s(dB)}{10}\right)} \quad ; \text{ and } \quad A_p = 10^{\left(\frac{A_p(dB)}{10}\right)}$$

The Chebychev equation is rewritten with the dB substitutions as

$$10^{\left(\frac{A_s(dB)}{10}\right)} - 1 = \left(10^{\left(\frac{A_p(dB)}{10}\right)} - 1\right)\left\{\cosh\left(n \cosh^{-1}\lambda\right)\right\}^2$$

This equation may be rearranged to solve for either $A_s(dB)$, $\lambda$, or $n$

$$1)\ A_s(dB) = 10 \log_{10}\left\{\left(10^{\frac{A_p(dB)}{10}} - 1\right)\left\{\cosh\left(n \cosh^{-1}\lambda\right)\right\}^2 + 1\right\}$$

or

$$2)\ \lambda = \cosh\left[\frac{1}{n}\cosh^{-1}\left\{\frac{10^{\frac{A_s(dB)}{10}} - 1}{10^{\frac{A_p(dB)}{10}} - 1}\right\}^{1/2}\right]$$

# Program Description I

or

$$3)\quad n = \frac{\cosh^{-1}\left\{\dfrac{10^{A_s(dB)/10} - 1}{10^{A_p(dB)/10} - 1}\right\}^{1/2}}{\cosh^{-1}\lambda}$$

As examples , this program will be used to compare against the filter orders obtained using the nomographs in the examples shown on page 2 of 9 in the program "Butterworth and Chebychev Lowpass Normalized Coefficients".

Highpass filter example:

Type: Butterworth (key [f] [a] )

$Ap_{dB}$ = 3 (key [3] [A] )

$As_{dB}$ = 40 ( key [4] [0] [B] )

$\lambda$ = 2 ( key [2] [D] )

Answer: n = 6.65 , use n = 7

Bandpass filter example:

Type: Chebychev ( key [f] [B] )

$Ap_{dB}$ = 1 ( key [1] [A]

$As_{dB}$ = 40 ( key [4] [0] [B] )

$\lambda$ = 2 ( key [2] [D] )

Answer: n = 4.54 , use n = 5

# Program Description I

Bandstop example

Type: Butterworth ( key [f] [a] )

$Ap_{dB}$ = 3 ( key [3] [A] )

$As_{dB}$ = 60 ( key [6] [0] [B] )

$\lambda$ = 10 ( key [1] [0] [D] )

Answer: n = 3.001

This example may be continued to demonstrate the other parts of the program. If the integral n is entered, the actual $\lambda$ where $As_{dB}$ occurs is calculated, or if $\lambda$ is entered, $As_{dB}$ will be calculated.

To calculate $\lambda$, given n: n = 3 ( key [3] [C] )

Answer: $\lambda$ = 10.0079

To calculate $As_{dB}$, given $\lambda$: $\lambda$ = 10. (key [1] [0] [E] )

Answer: $As_{dB}$ = 59.9794

One may use this program, or the nomographs to obtain the various filter parameters. If one does any amount of trading off of parameters, the nomographs will probably prove faster. If fine tuning of the nomograph results is desired i.e., greater numerical precision, then use this program.

# User Instructions

| | | | | | |
|---|---|---|---|---|---|
| | Butterworth | Chebychev | | | |
| [f] | $A_p$ (dB) | $A_s$(dB) | $n \to \lambda$ | $\lambda \to n$ | $\lambda \to A_s$ |

2

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1 | LOAD PROGRAM | | | | |
| 2 | KEY IN $A_p$ IN dB | $A_p$(dB) | | A | |
| 3 | KEY IN $A_s$ IN dB | $A_s$(dB) | | B | |
| 4 | SELECT BUTTERWORTH OR CHEBYCHEV | | f | A | |
| | a) BUTTERWORTH | | f | B | |
| | b) CHEBYCHEV | | | | |
| 5 | TO FIND $n$ GIVEN $\lambda$ | $\lambda$ | | D | $n$ |
| 6 | TO FIND $\lambda$ GIVEN $n$ | $n$ (integer) | | C | $\lambda$ |
| 7 | AFTER FINDING $n$, TO FIND $A_s$(dB) GIVEN $\lambda$ | | | | |
| | a) PERFORM STEP 6 TO STORE $n$ | | | | |
| | b) KEY IN $\lambda$ | $\lambda$ | | E | $A_s$(dB) |
| | STEP 7b MAY BE REPEATED WITH OTHER VALUES OF $\lambda$ WITHOUT HAVING TO REPEAT STEP 7a | | | | |

| LABELS | | | | | FLAGS |
|---|---|---|---|---|---|
| A enter $A_p$ in dB | B enter $A_s$ in dB | C $n \to \lambda$ | D $\lambda \to n$ | E $\lambda \to A_s$ | 0 |
| a | b | c | d | e | 1 clr = Chebychev set = Butterworth |
| 0 convert dB to $\lvert\ \rvert^2 - 1$ | 1 cosh subroutine | 2 $\cosh^{-1}$ subroutine | 3 | 4 | 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 2 |

# 97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | key in Ap in dB. convert to $\lvert\ \rvert^2-1$ store |
| 002 | GSB0 | 23 00 | |
| 003 | STO1 | 35 01 | |
| 004 | RTN | 24 | |
| 005 | *LBLB | 21 12 | key in As in dB convert to $\lvert\ \rvert^2-1$ store |
| 006 | GSB0 | 23 00 | |
| 007 | STO2 | 35 02 | |
| 008 | RTN | 24 | |
| 009 | *LBL0 | 21 00 | convert dB to magnitude squared minus one ($\lvert\ \rvert^2-1$) |
| 010 | 1 | 01 | |
| 011 | 0 | 00 | |
| 012 | ÷ | -24 | |
| 013 | $10^x$ | 16 33 | |
| 014 | 1 | 01 | |
| 015 | - | -45 | |
| 016 | RTN | 24 | |
| 017 | *LBLC | 21 13 | key in n the filter order. |
| 018 | STO3 | 35 03 | |
| 019 | RCL2 | 36 02 | |
| 020 | RCL1 | 36 01 | |
| 021 | ÷ | -24 | |
| 022 | √X | 54 | |
| 023 | F1? | 16 23 01 | |
| 024 | GTO3 | 22 03 | |
| 025 | GSB2 | 23 02 | |
| 026 | RCL3 | 36 03 | |
| 027 | ÷ | -24 | |
| 028 | GSB1 | 23 01 | |
| 029 | STO4 | 35 04 | |
| 030 | RTN | 24 | λ displayed for Chebychev |
| 031 | *LBL3 | 21 03 | |
| 032 | RCL3 | 36 03 | |
| 033 | 1/X | 52 | |
| 034 | $Y^x$ | 31 | |
| 035 | STO4 | 35 04 | λ displayed for Butterworth |
| 036 | RTN | 24 | |
| 037 | *LBLD | 21 14 | key in λ |
| 038 | STO4 | 35 04 | |
| 039 | RCL2 | 36 02 | |
| 040 | RCL1 | 36 01 | |
| 041 | ÷ | -24 | |
| 042 | √X | 54 | |
| 043 | F1? | 16 23 01 | |
| 044 | GTO3 | 22 03 | |
| 045 | GSB2 | 23 02 | |
| 046 | RCL4 | 36 04 | |
| 047 | GSB2 | 23 02 | |
| 048 | ÷ | -24 | |
| 049 | STO3 | 35 03 | |
| 050 | RTN | 24 | n displayed for Chebychev |
| 051 | *LBL3 | 21 03 | |
| 052 | LN | 32 | |
| 053 | RCL4 | 36 04 | |
| 054 | LN | 32 | |
| 055 | ÷ | -24 | n displayed for Butterworth |
| 056 | STO3 | 35 03 | |
| 057 | RTN | 24 | |
| 058 | *LBLE | 21 15 | key in λ |
| 059 | F1? | 16 23 01 | |
| 060 | GTO3 | 22 03 | |
| 061 | GSB2 | 23 02 | |
| 062 | RCL3 | 36 03 | |
| 063 | × | -35 | |
| 064 | GSB1 | 23 01 | |
| 065 | GTO4 | 22 04 | |
| 066 | *LBL3 | 21 03 | |
| 067 | RCL3 | 36 03 | |
| 068 | $Y^x$ | 31 | |
| 069 | *LBL4 | 21 04 | |
| 070 | $X^2$ | 53 | |
| 071 | RCL1 | 36 01 | |
| 072 | × | -35 | |
| 073 | 1 | 01 | |
| 074 | + | -55 | |
| 075 | LOG | 16 32 | |
| 076 | 1 | 01 | |
| 077 | 0 | 00 | |
| 078 | × | -35 | |
| 079 | RTN | 24 | As(dB) displayed |
| 080 | *LBL1 | 21 01 | Cosh subroutine |
| 081 | $e^x$ | 33 | |
| 082 | ENT↑ | -21 | |
| 083 | 1/X | 52 | |
| 084 | + | -55 | |
| 085 | 2 | 02 | |
| 086 | ÷ | -24 | |
| 087 | RTN | 24 | |
| 088 | *LBL2 | 21 02 | Arc Cosh subroutine |
| 089 | ENT↑ | -21 | |
| 090 | $X^2$ | 53 | |
| 091 | 1 | 01 | |
| 092 | - | -45 | |
| 093 | √X | 54 | |
| 094 | + | -55 | |
| 095 | LN | 32 | |
| 096 | RTN | 24 | |
| 097 | *LBLa | 21 16 11 | set flag 1 to indicate Butterworth |
| 098 | SF1 | 16 21 01 | |
| 099 | RTN | 24 | |
| 100 | *LBLb | 21 16 12 | Clear flag 1 to indicate Chebychev |
| 101 | CF1 | 16 22 01 | |
| 102 | RTN | 24 | |
| 110 | | | |

REGISTERS

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| | $A_p^2-1$ | $A_s^2-1$ | $n$ | $\lambda$ | | | | | |
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| | | | | | | | | | |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| | | | | | |

# Program Description I

Program Title: BUTTERWORTH AND CHEBYCHEV LOWPASS NORMALIZED COEFFICIENTS

Contributor's Name: BRUCE K MURDOCK
Address: 6875 SABADO TARDE RD
City: GOLETA State: CALIF Zip Code: 93017

Program Description, Equations, Variables: THIS PROGRAM GENERATES THE NORMALIZED (1 OHM, 1 RADIAN/SECOND) ALL POLE LOWPASS ELEMENT VALUES FOR EITHER THE BUTTERWORTH (MAXIMALLY FLAT) OR CHEBYCHEV (EQUAL PASSBAND RIPPLE) AMPLITUDE APPROXIMATIONS. THESE NORMALIZED LOWPASS VALUES ARE ALSO STORED IN THE SECONDARY REGISTERS FOR USE BY THE TRANSFORMATION PROGRAMS CONTAINED ON OTHER MAGNETIC CARDS

THE BUTTERWORTH VALUES COME FROM BENNETT'S FORMULA

$$g_k = 2 \sin\left\{\frac{2k-1}{2n}\pi\right\} \qquad k = 1, 2, \ldots, n$$

$n$ = FILTER ORDER

ARGUMENT IS IN RADIANS

THE CHEBYCHEV VALUES ARE GENERATED USING A SET OF RECURSION FORMULAS FOUND IN WHITE'S BOOK

$$g_k = 4(a_k \cdot a_{k-1}) / (b_{k-1} \cdot g_{k-1}); \; k = 1, 2 \ldots, n$$

$$a_k = \sin\left\{\frac{2k-1}{2n}\pi\right\}$$

$$b_k = \gamma^2 + \sin^2\left\{\frac{k}{n}\pi\right\}$$

$$\gamma = \sinh\left\{\frac{1}{2n}\left[\ln\left(\frac{y + 1/y}{y - 1/y}\right)\right]\right\}; \; y = 10^{\left(\frac{\epsilon_{dB}}{40}\right)}$$

WHERE $\epsilon_{dB}$ = PASSBAND RIPPLE IN DB,

$$\epsilon = \left(10^{\left(\frac{\epsilon_{dB}}{10}\right)} - 1\right)^{1/2}, \text{ AND}$$

$$\omega_{-3dB} \text{ (RADIANS/SEC)} = \cosh\left\{\frac{1}{n}\cosh^{-1}\frac{1}{\epsilon}\right\}$$

# Program Description I

TO USE THE PROGRAM, ONE NEEDS TO ENTER THE ORDER OF THE FILTER, $n$, AND IF CHEBYCHEV RESPONSE IS DESIRED, THE PASSBAND RIPPLE IN DB. AN EASY WAY TO OBTAIN THESE PARAMETERS IS TO USE THE KAWAKAMI NOMOGRAPHS

THESE NOMOGRAPHS HAVE BEEN REDERIVED ABOUT THE REGION OF INTEREST COVERED BY THESE PROGRAMS IN FIGURES 1 AND 2

NORMALIZED LOWPASS ELEMENTS AND NOMOGRAPHS ARE USED BECAUSE THE SPECIFICATIONS FOR OTHER FILTER TYPES MAY BE EASILY CONVERTED TO EQUIVALENT SPECIFICATIONS FOR A NORMALIZED LOWPASS.

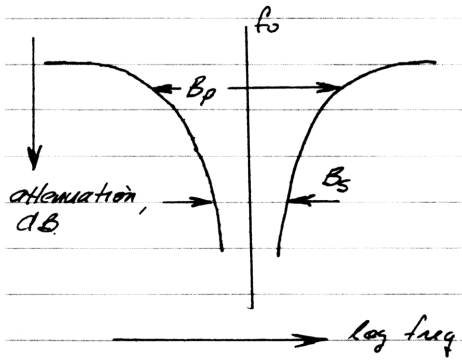
HIGHPASS CONVERSION: THE EQUIVALENT LOWPASS REQUIREMENTS ARE OBTAINED BY INVERTING THE HIGHPASS REQUIREMENTS. EXAMPLE: ASSUME A HIGHPASS FILTER WITH BUTTERWORTH RESPONSE IS REQUIRED TO PASS 20 KHZ WITH 3 dB OR LESS ATTENUATION, BUT REJECT FREQUENCIES BELOW 10 KHZ WITH AT LEAST 40 dB ATTENUATION. ONE MAY USE THE KAWAKAMI NOMOGRAPH FOR BUTTERWORTH WITH $\lambda = 20\,KHz/10\,KHz = 2$, $A_{MAX} = 3\,dB$, AND $A_{MIN} = 40\,dB$ TO OBTAIN $n = 6.7$. SINCE N MUST BE AN INTEGER, USE $n = 7$. THE LOWPASS TO HIGHPASS TRANSFORMATION IS COVERED IN THE PROGRAM DESCRIPTION IN THE LOWPASS TO HIGHPASS DE-NORMALIZING PROGRAM.

BANDPASS CONVERSION: THE BANDWIDTH OF A BANDPASS FILTER CORRESPONDS TO THE CUTOFF FREQUENCY OF THE LOWPASS CASE. THIS IMPLIES THAT BANDPASS RATIOS ARE PRESERVED IN THE LOWPASS CASE. EXAMPLE: A BANDPASS FILTER IS NEEDED TO PASS A 20 KHZ BAND OF INFORMATION WITHIN $\pm$ 1/2 dB AT A CENTER FREQUENCY OF 100 KHZ. THE FILTER SHOULD HAVE A -40 dB BANDWIDTH OF 40 KHZ OR LESS. ONE MAY USE THE KAWAKAMI NOMOGRAPH

# Program Description I

FOR CHEBYCHEV FILTERS WITH $\lambda$ = 40 KHz/20KHz = 2, A MAX = 1 dB (± 1/2 dB), AND A MIN = 40 TO OBTAIN n = 4.4. N MUST BE INTEGRAL, USE n = 5. THE LOWPASS TO BANDPASS TRANSFORMATION IS COVERED IN THE PROGRAM DESCRIPTION OF THE PROGRAM FOR BANDPASS TRANSFORMATION

BAND REJECT FILTER CONVERSION: BAND REJECT FILTERS ARE THE OPPOSITE OF BANDPASS FILTERS. THESE FILTERS ARE ALSO CALLED BAND STOP FILTERS.




HERE Bp IS THE PASSBAND AND Bs IS THE STOPBAND. ON A LOG FREQUENCY SCALE THE RESPONSE WILL BE SYMMETRICAL ABOUT THE CENTER FREQUENCY AS IN THE BAND PASS CASE. HERE, HOWEVER, $\lambda$ = Bp/Bs.

EXAMPLE: DESIGN A BANDSTOP FILTER CENTERED AT 20 KHz. IT SHOULD HAVE A 3 dB BANDWIDTH NO GREATER THAN 10 KHz, AND A 60 dB BANDWIDTH NO GREATER THAN 1000 Hz. THE FILTER SHAPE SHOULD BE MONOTONIC (NO RIPPLES) THEREFORE THE BUTTERWORTH RESPONSE WILL BE USED. THE KAWAKAMI NOMOGRAPH FOR BUTTERWORTH WITH $\lambda$ = 10000/1000 = 10, A MAX = 3dB, AND A MIN = 60 dB SHOWS n = 3 IS REQUIRED.

THE MAXIMUM FILTER ORDER THAT THIS PROGRAM CAN ACCEPT IS TWELVE (12). THIS LIMITATION RESULTS FROM THE STORAGE SPACE AVAILABLE FOR THESE COEFFICIENTS.

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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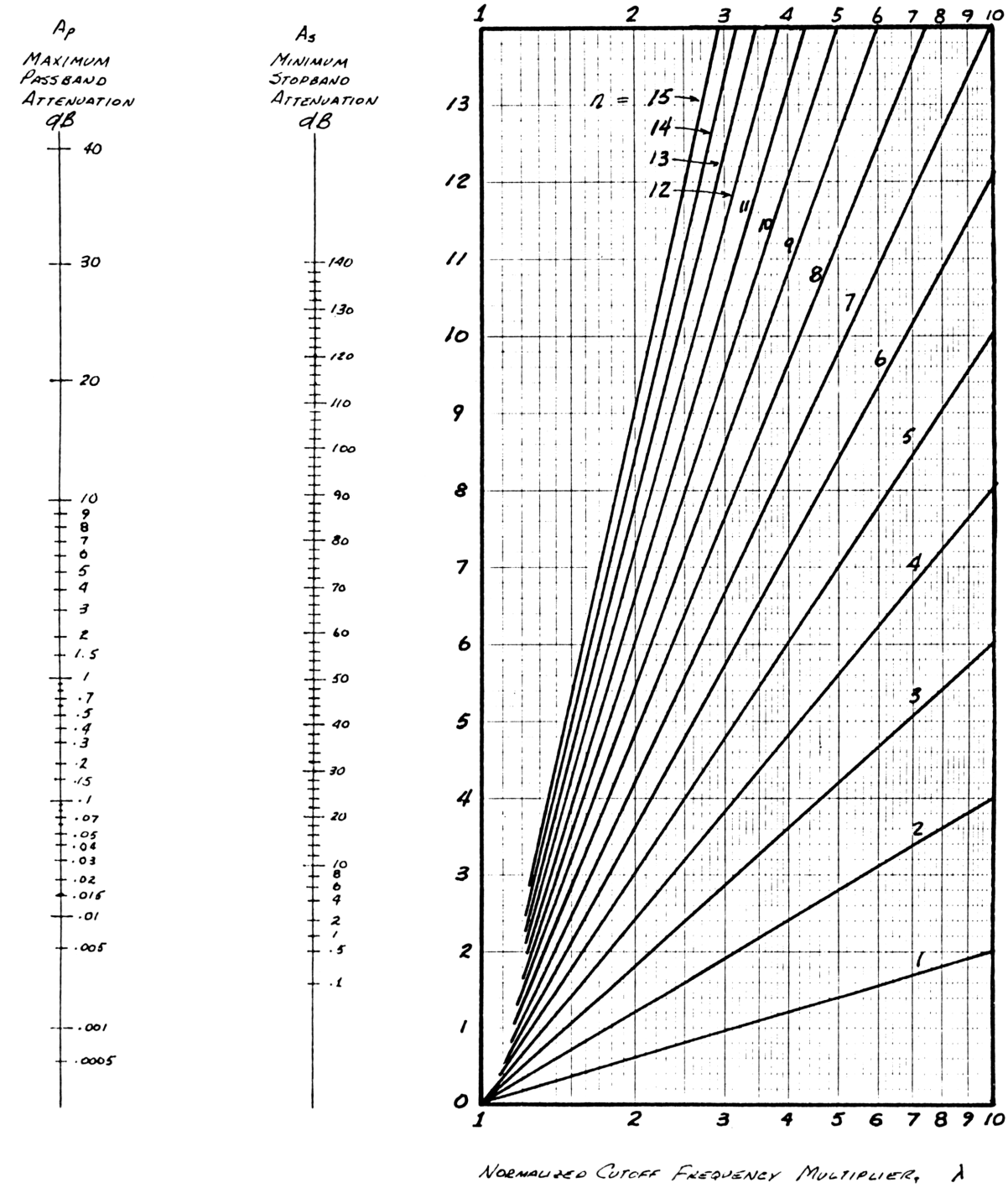
# Program Description I

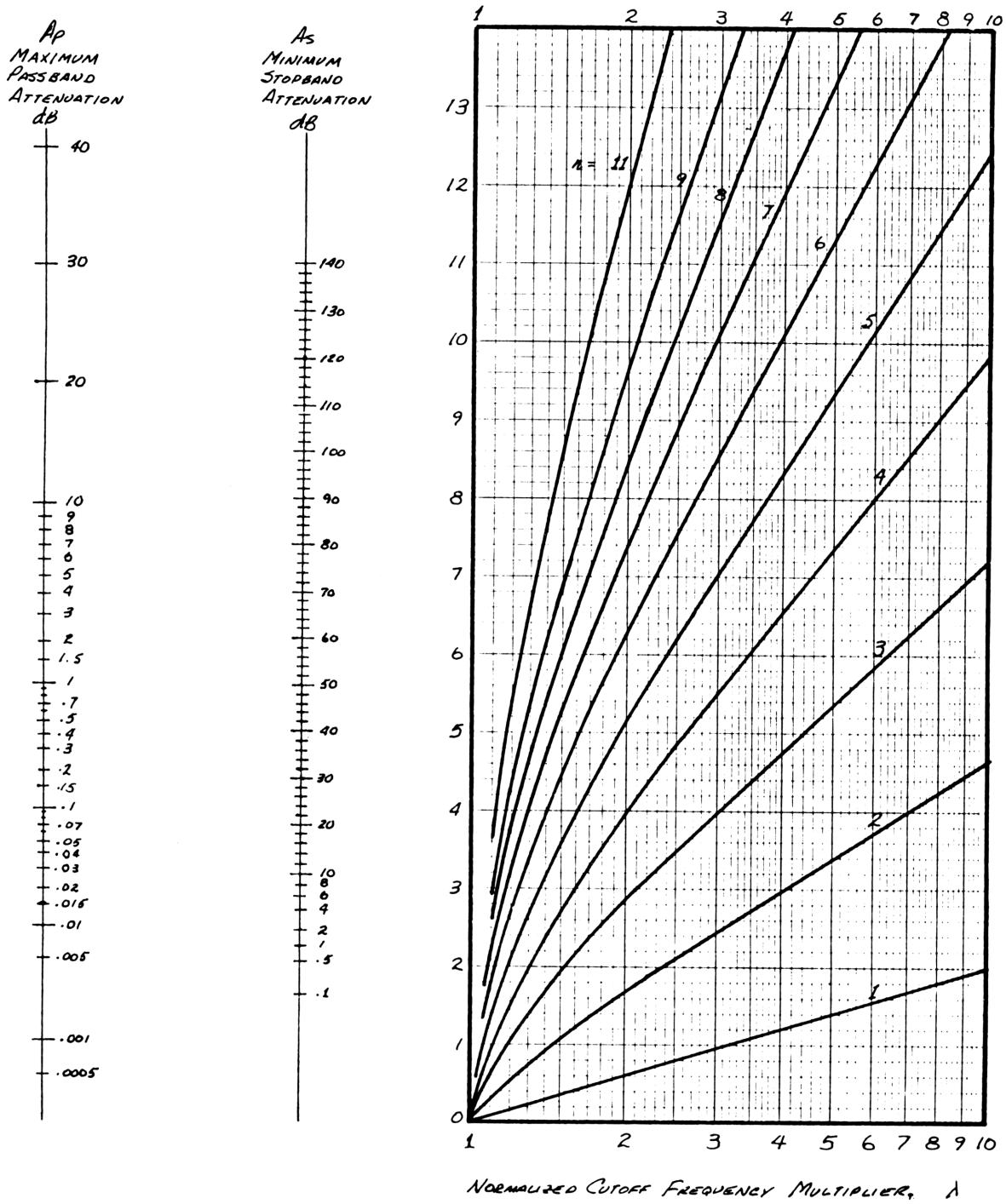



BUTTERWORTH FILTER NOMOGRAPH

$$A_s^2 - 1 = (A_p^2 - 1)\lambda^{2n}$$

FIGURE 1

# Program Description I




CHEBYCHEF FILTER NOMOGRAPH

$$A_s^2 - 1 = (A_p^2 - 1)\{\cosh(n \cosh^{-1} \lambda)\}^2$$

FIGURE 2

# Program Description I

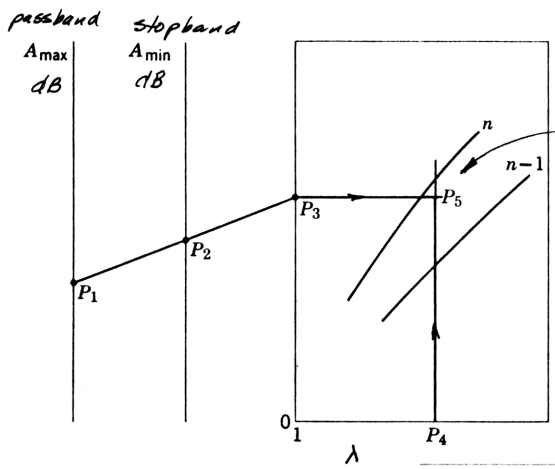
**Program Title** BUTTERWORTH AND CHEBYCHEV NORMALIZED LOWPASS COEFFICIENTS

**Contributor's Name**

**Address**

**City** **State** **Zip Code**

**Program Description, Equations, Variables**




n must be integral ∴ choose next larger n. preferrably, n should be odd

$$\lambda = \frac{f_{stopband}}{f_{passband}}$$

$P_1$ and $P_2$ are the required passband and stopband attenuation $P_3$ is a turning point, $P_4$ represents the frequency ratio between $A_{min}$ stopband and $A_{max}$ passband. $P_5$ is the nomograph output and represents the required filter order.

**Operating Limits and Warnings** THESE SAME NOMOGRAPHS ARE CONTAINED IN ZVEREV, HOWEVER, THE $A_{MIN}$ SCALE APPEARS TO BE MISREGISTERED BY ABOUT 2 dB, HENCE, THESE ZVEREV NOMOGRAPHS GIVE INACCURATE RESULTS.

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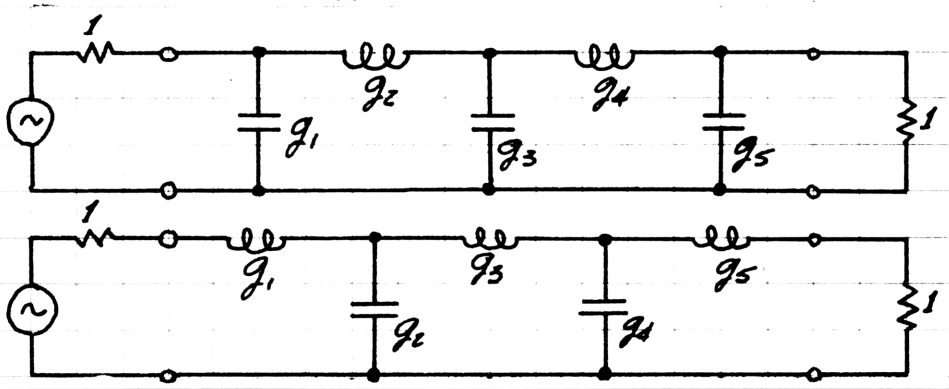
# Program Description II

**Sketch(es)**

These two forms are dual of one-another. Both forms will exhibit the same filter response.




**Sample Problem(s)** FIND THE NORMALIZED LOWPASS COEFFICIENTS FOR A 1 dB RIPPLE, 5th ORDER CHEBYCHEV FILTER. THIS FILTER WILL BE 1dB DOWN AT $\omega = 1$, THE BANDEDGE. ALSO FIND THE COEFFICIENTS SUCH THAT THE FILTER IS -3dB AT THE BANDEDGE

1) READ IN BOTH SIDES OF THE MAGNETIC CARD
2) KEY IN $n = 5$ AND ENTER INTO PROGRAM, [5], [A].
3) KEY IN $\epsilon_{dB} = 1$ AND COMPUTE COEFFICIENTS, [1], [B].
4) PRINTER WILL PRINT THE $\omega$ WHERE $\alpha(\omega) = -3dB$ FOLLOWED BY THE LOWPASS NORMALIZED COEFFIENTS ($\alpha(1) = -\epsilon_{dB}$) THESE COEFFICIENTS WILL ALSO BE STORED AUTOMATICALLY.
5) TO CONVERT COEFFICIENTS SO $\alpha(1) = -3dB$, KEY [f], [B] THE PRINTER WILL OUTPUT THE NEW COEFFICIENTS AND THEY WILL ALSO REPLACE THE STORED VALUES

**Solution(s)**

```
n     =  5.000000 GSBA
ε_dB  =  1.000000 GSBB
         1.033815  *** = ω_-3dB

         2.134882  *** = g5
         1.091107  *** = g4
         3.000923  *** = g3
         1.091107  *** = g2
         2.134882  *** = g1
```

Convert Coefficients so $\alpha(1) = -3dB$ GSBb

```
         2.207072  *** = g5'
         1.128003  *** = g4'
         3.102398  *** = g3'
         1.128003  *** = g2'
         2.207072  *** = g1'
```

**Reference(s)**
- DONALD R.J. WHITE "A HANDBOOK ON ELECTRICAL FILTERS"
- ZVEREV, "HANDBOOK OF FILTER SYNTHESIS", J WILEY 1967
- KAWAKAMI, "NOMOGRAPHS FOR BUTTERWORTH AND CHEBYSHEV FILTERS" IEEE TRANSACTIONS ON CIRCUIT THEORY, VOL CT-10, JUNE 1963

# User Instructions

| | | | | | |
|---|---|---|---|---|---|
| Butterworth | Convert Chebychev -3dB@ w=1 | $\sinh^{-1}(x)$ | $\cosh^{-1}(x)$ | $\tanh^{-1}(x)$ | 2 |
| n | Chebychev $\epsilon_{dB}$ | $\sinh(x)$ | $\cosh(x)$ | $\tanh(x)$ | |

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1 | READ IN CARD, BOTH SIDES | | | | |
| 2 | KEY IN n, THE FILTER ORDER (must be odd in the Chebychev case if the bandpass transformation programs are used) | n | | A | |
| 3 | FOR BUTTERWORTH COEFFICIENTS (GO TO NEXT STEP FOR CHEBYCHEV COEFFICIENTS) | | f | A | $g_n$<br>$g_{n-1}$<br>⋮<br>$g_1$ |
| 4 | FOR CHEBYCHEV COEFFICIENTS, KEY IN $\epsilon_{dB}$, THE PASSBAND RIPPLE IN DECIBELS. THE FILTER WILL BE DOWN $\epsilon_{dB}$ AT $\omega = 1$ RADIAN/SEC | $\epsilon_{dB}$ | | B | $\omega_{-3dB}$<br>Space<br>$g_n$<br>$g_{n-1}$<br>⋮<br>$g_1$ |
| 5 | TO CHANGE CHEBYCHEV COEFFICIENTS SO FILTER WILL BE -3dB DOWN AT $\omega = 1$ RADIAN/SEC | | f | B | $g_n'$<br>$g_{n-1}'$<br>⋮<br>$g_1'$ |
| 6 | HYPERBOLIC FUNCTIONS. A FEW OF THESE ARE USED AS SUBROUTINES IN THE CHEBYCHEV PROGRAM. THEY MAY ALSO BE USED INDEPENDANTLY | x<br>x<br>x<br>x<br>x<br>x | | C<br>D<br>E<br>f C<br>f D<br>f E | $\sinh(x)$<br>$\cosh(x)$<br>$\tanh(x)$<br>$\sinh^{-1}(x)$<br>$\cosh^{-1}(x)$<br>$\tanh^{-1}(x)$ |

# 97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | |
| 002 | STO6 | 35 06 | store n |
| 003 | 1/X | 52 | generate and store π/n |
| 004 | PI | 16-24 | |
| 005 | × | -35 | |
| 006 | STO1 | 35 01 | |
| 007 | GSB9 | 23 09 | initialize regs 3,5,7,8&9 |
| 008 | RTN | 24 | |
| 009 | *LBLB | 21 12 | CHEBYCHEV COEFFICIENTS |
| 010 | STO9 | 35 09 | store $\epsilon_{dB}$ |
| 011 | 1 | 01 | calculate ε |
| 012 | 0 | 00 | |
| 013 | ÷ | -24 | |
| 014 | 10^x | 16 33 | |
| 015 | 1 | 01 | |
| 016 | - | -45 | |
| 017 | √X | 54 | |
| 018 | 1/X | 52 | calculate $\cosh^{-1}\frac{1}{\epsilon}$ |
| 019 | GSBd | 23 16 14 | |
| 020 | RCL6 | 36 06 | calculate $\omega_{-3dB} = \cosh\left(\frac{1}{n}\cosh^{-1}\frac{1}{\epsilon}\right)$ |
| 021 | ÷ | -24 | |
| 022 | GSBD | 23 14 | |
| 023 | STO0 | 35 00 | store & print $\omega_{-3dB}$ |
| 024 | PRTX | -14 | |
| 025 | RCL9 | 36 09 | calculate γ |
| 026 | SFC | 16-11 | |
| 027 | ENT↑ | -21 | |
| 028 | 4 | 04 | |
| 029 | 0 | 00 | |
| 030 | ÷ | -24 | |
| 031 | 10^x | 16 33 | |
| 032 | ENT↑ | -21 | |
| 033 | ENT↑ | -21 | |
| 034 | ENT↑ | -21 | |
| 035 | 1/X | 52 | |
| 036 | + | -55 | |
| 037 | R↓ | -31 | |
| 038 | R↓ | -31 | |
| 039 | 1/X | 52 | |
| 040 | - | -45 | |
| 041 | ÷ | -24 | |
| 042 | LN | 32 | |
| 043 | RCL6 | 36 06 | |
| 044 | 2 | 02 | |
| 045 | × | -35 | |
| 046 | ÷ | -24 | |
| 047 | GSBC | 23 13 | |
| 048 | STO4 | 35 04 | |
| 049 | X² | 53 | |
| 050 | STO2 | 35 02 | |
| 051 | GSB9 | 23 09 | initialize registers |
| 052 | *LBL2 | 21 02 | Chebychev recursion loop |
| 053 | RCL5 | 36 05 | $a_{k-1}$ |
| 054 | RCL1 | 36 01 | |
| 055 | 2 | 02 | |
| 056 | ÷ | -24 | |
| 057 | RCL8 | 36 08 | |
| 058 | × | -35 | |
| 059 | SIN | 41 | $a_k$ |
| 060 | STO5 | 35 05 | |
| 061 | × | -35 | |
| 062 | RCL3 | 36 03 | $b_{k-1}$ |
| 063 | RCL4 | 36 04 | $g_{k-1}$ |
| 064 | × | -35 | |
| 065 | ÷ | -24 | |
| 066 | 4 | 04 | |
| 067 | × | -35 | |
| 068 | STO4 | 35 04 | $g_k = 4\frac{a_k \cdot a_{k-1}}{b_{k-1} \cdot g_{k-1}}$ |
| 069 | RCL2 | 36 02 | |
| 070 | RCL1 | 36 01 | |
| 071 | RCL7 | 36 07 | |
| 072 | × | -35 | |
| 073 | SIN | 41 | |
| 074 | X² | 53 | |
| 075 | + | -55 | |
| 076 | STO3 | 35 03 | $b_k$ |
| 077 | GSB8 | 23 08 | store $g_k$ and test for loop exit |
| 078 | X≠Y? | 16-35 | |
| 079 | GTO2 | 22 02 | |
| 080 | SFC | 16-11 | loop exit |
| 081 | RTN | 24 | |
| 082 | *LBLa | 21 16 11 | BUTTERWORTH COEFS |
| 083 | GSB9 | 23 09 | initialize registers |
| 084 | SFC | 16-11 | |
| 085 | *LBL0 | 21 00 | |
| 086 | RCL8 | 36 08 | |
| 087 | RCL1 | 36 01 | |
| 088 | 2 | 02 | |
| 089 | ÷ | -24 | |
| 090 | × | -35 | |
| 091 | SIN | 41 | |
| 092 | 2 | 02 | |
| 093 | × | -35 | |
| 094 | STO4 | 35 04 | $g_k = 2\sin\left(\frac{2k-1}{2n}\pi\right)$ |
| 095 | GSB8 | 23 08 | Store $g_k$ & test for loop exit |
| 096 | X≠Y? | 16-35 | |
| 097 | GTO0 | 22 00 | |
| 098 | SFC | 16-11 | |
| 099 | RTN | 24 | |
| 100 | *LBL8 | 21 08 | coefficient store and print subroutine |
| 101 | RCL7 | 36 07 | |
| 102 | 9 | 09 | |
| 103 | + | -55 | |
| 104 | STOI | 35 46 | |
| 105 | RCL4 | 36 04 | |
| 106 | PRTX | -14 | |
| 107 | STOI | 35 45 | |
| 108 | 1 | 01 | |
| 109 | ST+7 | 35-55 07 | |
| 110 | 2 | 02 | |
| 111 | ST+8 | 35-55 08 | |
| 112 | RCL6 | 36 06 | |

## REGISTERS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 $\omega_{-3dB}$ | 1 $\pi/n$ | 2 $\gamma^2$ | 3 $b_{k-1}$ | 4 $g_{k-1}$ | 5 $a_{k-1}$ | 6 $n$ | 7 $k$ | 8 $2k-1$ | 9 $\epsilon_{dB}$ |
| S0 $g_n$ | S1 $g_{n-1}$ | S2 $g_{n-2}$ | S3 $g_{n-3}$ | S4 $g_{n-4}$ | S5 $g_{n-5}$ | S6 $g_{n-6}$ | S7 $g_{n-7}$ | S8 $g_{n-8}$ | S9 $g_{n-9}$ |

| | | | | | |
|---|---|---|---|---|---|
| A $g_{n-10}$ | B $g_{n-11}$ | C $g_{n-12}$ | D used | E used | I index |

# '97 Program Listing II

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 113 | 2 | 02 | |
| 114 | × | -35 | |
| 115 | RCL8 | 36 08 | |
| 116 | RTN | 24 | |
| 117 | *LBL9 | 21 09 | Register initialization subroutine |
| 118 | P⇄S | 16-51 | |
| 119 | CLRG | 16-53 | |
| 120 | P⇄S | 16-51 | |
| 121 | 1 | 01 | |
| 122 | STO5 | 35 05 | |
| 123 | STO7 | 35 07 | |
| 124 | STO8 | 35 08 | |
| 125 | 2 | 02 | |
| 126 | STO3 | 35 03 | |
| 127 | RTN | 24 | |
| 128 | *LBLC | 21 13 | Sinh(x) |
| 129 | $e^x$ | 33 | |
| 130 | ENT↑ | -21 | |
| 131 | 1/X | 52 | |
| 132 | - | -45 | |
| 133 | 2 | 02 | |
| 134 | ÷ | -24 | |
| 135 | RTN | 24 | |
| 136 | *LBLD | 21 14 | Cosh(x) |
| 137 | $e^x$ | 33 | |
| 138 | ENT↑ | -21 | |
| 139 | 1/X | 52 | |
| 140 | + | -55 | |
| 141 | 2 | 02 | |
| 142 | ÷ | -24 | |
| 143 | RTN | 24 | |
| 144 | *LBLE | 21 15 | Tanh(x) |
| 145 | STOE | 35 15 | |
| 146 | GSBC | 23 13 | |
| 147 | RCLE | 36 15 | |
| 148 | GSBD | 23 14 | |
| 149 | ÷ | -24 | |
| 150 | RTN | 24 | |
| 151 | *LBLa | 21 16 13 | $Sinh^{-1}(x)$ |
| 152 | ENT↑ | -21 | |
| 153 | $X^2$ | 53 | |
| 154 | 1 | 01 | |
| 155 | + | -55 | |
| 156 | √X | 54 | |
| 157 | + | -55 | |
| 158 | LN | 32 | |
| 159 | RTN | 24 | |
| 160 | *LBLd | 21 16 14 | $Cosh^{-1}(x)$ |
| 161 | ENT↑ | -21 | |
| 162 | $X^2$ | 53 | |
| 163 | 1 | 01 | |
| 164 | - | -45 | |
| 165 | √X | 54 | |
| 166 | + | -55 | |
| 167 | LN | 32 | |
| 168 | RTN | 24 | |
| 169 | *LBLe | 21 16 15 | $Tanh^{-1}(x)$ |
| 170 | STOE | 35 15 | |
| 171 | 1 | 01 | |
| 172 | + | -55 | |
| 173 | LN | 32 | |
| 174 | 2 | 02 | |
| 175 | ÷ | -24 | |
| 176 | 1 | 01 | |
| 177 | RCLE | 36 15 | |
| 178 | - | -45 | |
| 179 | LN | 32 | |
| 180 | 2 | 02 | |
| 181 | ÷ | -24 | |
| 182 | - | -45 | |
| 183 | RTN | 24 | |
| 184 | *LBLb | 21 16 12 | Convert Chebychev Coefficients from $\alpha(1) = \epsilon_{dB}$ to $\alpha(1) = -3dB$ |
| 185 | 1 | 01 | |
| 186 | STO7 | 35 07 | |
| 187 | SPC | 16-11 | |
| 188 | *LBL3 | 21 03 | |
| 189 | RCL7 | 36 07 | |
| 190 | 9 | 09 | |
| 191 | ÷ | -55 | |
| 192 | STOI | 35 46 | |
| 193 | RCLI | 36 45 | |
| 194 | RCL0 | 36 00 | |
| 195 | × | -35 | |
| 196 | STOI | 35 45 | |
| 197 | PRTX | -14 | |
| 198 | 1 | 01 | |
| 199 | ST+7 | 35-55 07 | |
| 200 | RCL6 | 36 06 | |
| 201 | RCL7 | 36 07 | |
| 202 | X≠Y? | 16-35 | |
| 203 | GTO3 | 22 03 | |
| 204 | SPC | 16-11 | |
| 205 | RTN | 24 | |
| 210 | | | |
| 220 | | | |

## LABELS

| | | | | |
|---|---|---|---|---|
| A FILTER ORDER | B CHEBYCHEV COEFFICIENTS | C Sinh(x) | D Cosh(x) | E Tanh(x) |
| a BUTTERWORTH COEFFICIENTS | b CONVERT CHEBYCHEV | c $Sinh^{-1}(x)$ | d $Cosh^{-1}(x)$ | e $Tanh^{-1}(x)$ |
| 0 BUTTERWORTH LOOP POINT | 1 | 2 CHEBYCHEV LOOP POINT | 3 CHEV. CONVERT LOOP POINT | 4 |
| 5 | 6 | 7 | 8 OUTPUT & STORE ROUTINE | 9 INITIALIZATION ROUTINE |

## FLAGS

| | |
|---|---|
| 0 | |
| 1 | |
| 2 | |
| 3 | |

## SET STATUS

| FLAGS | ON | OFF | TRIG | | DISP | |
|---|---|---|---|---|---|---|
| 0 | ☐ | ☐ | DEG | ☐ | FIX | ■ |
| 1 | ☐ | ☐ | GRAD | ☐ | SCI | ☐ |
| 2 | ☐ | ☐ | RAD | ■ | ENG | ☐ |
| 3 | ☐ | ☐ | | | n | 6 |

# Program Description I

**Program Title** NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION FOR TYPES 1, 2, 6, AND 7

**Contributor's Name** BRUCE K MURDOCK

**Address** 6875 SABADO TARDE RD

**City** GOLETA **State** CALIF **Zip Code** 93017

**Program Description, Equations, Variables, etc.** THIS PROGRAM CONVERTS THE NORMALIZED LOWPASS FILTER ELEMENT VALUES TO ONE OR ALL OF FOUR BANDPASS FILTER TOPOLOGIES. THIS PROGRAM IS ONE OF A SET OF TRANSFORMATION PROGRAMS.

FIGURE 1 SHOWS THE FOUR BANDPASS TOPOLOGIES. TYPES 1 AND 2 ARE EXACT LOWPASS - BANDPASS TRANSFORMATIONS AND MAY BE USED WITH ANY LOADED Q. TYPES 6 AND 7 OF THIS SET AND TYPES 8, 9, 10, AND 11 OF THE COMPANION SET ARE NARROWBAND APPROXIMATIONS AND SHOULD ONLY BE USED IF THE LOADED Q IS GREATER THAN 5. THE LOADED Q IS DEFINED:

$$Q_L = \frac{f_0}{BW} = \frac{\text{FILTER CENTER FREQUENCY}}{\text{FILTER BANDWIDTH}}$$

FIGURE 2 IS A REPRODUCTION OF TABLE 7.2 FROM WHITE AND IS INTENDED TO BE A GUIDE AS TO THE FILTER TOPOLOGY THAT IS BEST SUITED FOR A PARTICULAR APPLICATION.

**Operating Limits and Warnings** THIS PROGRAM OBTAINS THE NORMALIZED LOWPASS ELEMENT VALUES FROM REGISTER STORAGE IN THE SECONDARY SET OF REGISTERS. OTHER FILTER PARAMETERS SUCH AS FILTER ORDER ARE ALSO STORED. ONE SHOULD RUN THE NORMALIZED LOWPASS ELEMENT PROGRAM FIRST, OR MANUALLY PLACE THE DESIRED NORMALIZED LOWPASS COEF'S IN SECONDARY STORAGE BEFORE RUNNING THIS PROGRAM

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description 1

**Program Title** NORMALIZED LOWPASS TO BANDPASS TRANSFORMATION TYPES 1, 2, 6, 7

**Contributor's Name** BRUCE K MURDOCK

**Address** 6875 SABADO TARDE RD

**City** GOLETA **State** CALIF **Zip Code** 93017

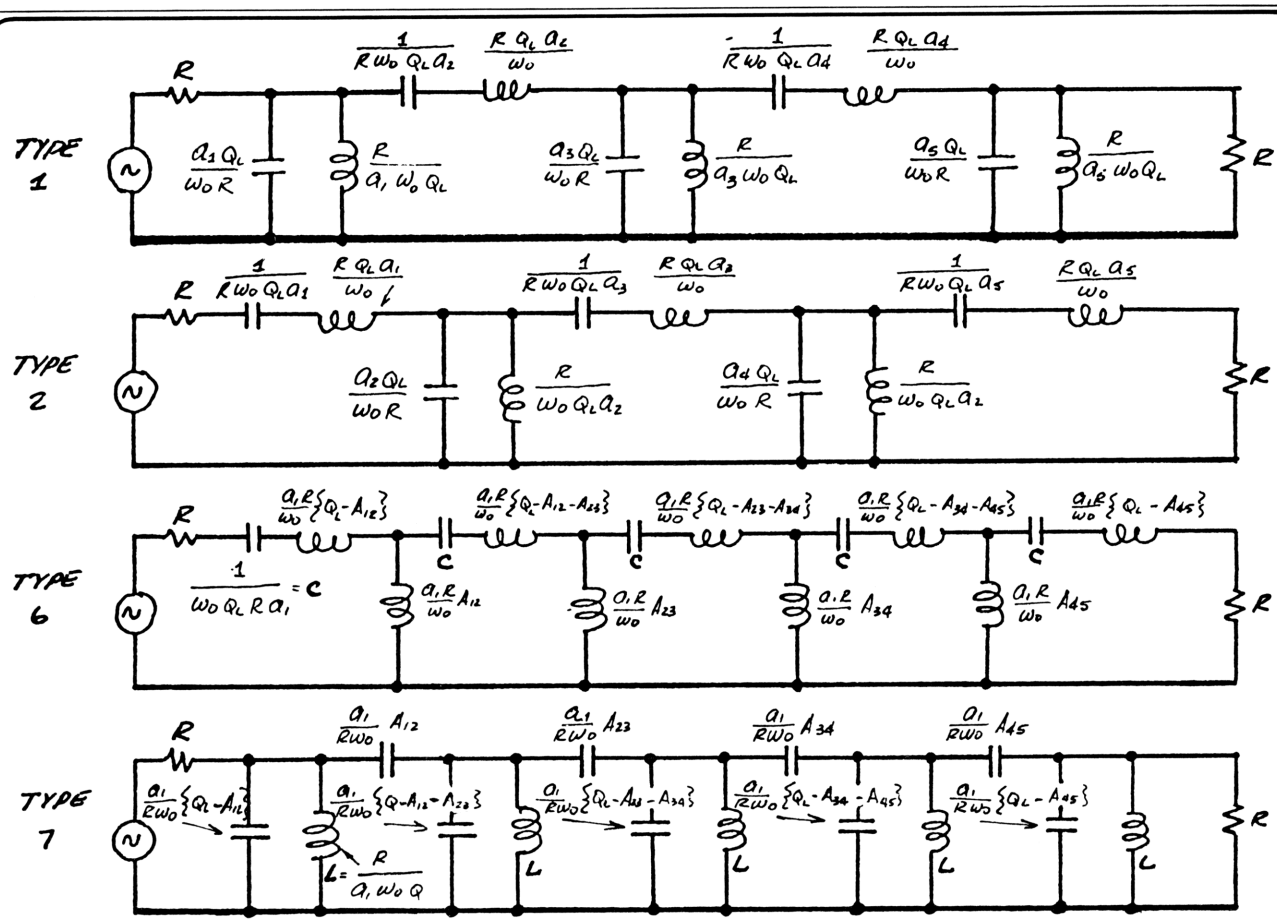


FIGURE 1 – BANDPASS TOPOLOGIES

$$Q_L = f_0/BW \quad ; \quad a_k \equiv g_k \quad : \quad A_{ij} = (a_i \cdot a_j)^{-1/2}$$

THE FILTER MUST HAVE EQUAL TERMINATION IMPEDANCES FOR THESE ROUTINES, HENCE, IF CHEBYCHEV RESPONSE IS DESIRED, THE FILTER ORDER MUST BE ODD. (EVEN ORDER CHEBYCHEV FILTERS HAVE UNEQUAL TERMINATION IMPEDANCES.

# Program Description I

THE LOWPASS NORMALIZED COEFFICIENTS MAY BE TRANSFORMED TO AN INFINITE VARIETY OF BANDPASS TOPOLOGIES. THE REASON FOR NEEDING MORE THAN ONE TRANSFORMATION IS PHYSICAL REALIZABILITY. FOR EXAMPLE, ONE WOULD NOT WANT TO END UP WITH A BANDPASS STRUCTURE CONTAINING 1 μF CAPACITORS WHEN THE OPERATING FREQUENCY IS 100 MEGAHERTZ.

D.R.J. WHITE HAS AUTHORED AN EXCELLENT FILTER DESIGN BOOK WHICH IS VERY PRACTICAL IN NATURE. ONE PROBLEM HE ADDRESSES, IN DETAIL, IS THIS PHYSICAL REALIZABILITY PROBLEM FOR BANDPASS, LOWPASS, AND HIGHPASS FILTERS. HE HAS DERIVED ELEVEN DIFFERENT BANDPASS TOPOLOGIES TO ALLOW FINDING A MIX OF COMPONENT VALUES THAT ARE REALIZABLE.

THE FOLLOWING FOUR DEFINATIONS OF ELEMENT PHYSICAL REALIZABILITY ARE ESTABLISHED:

1) READILY REALIZABLE (R)

$1\,\mu Hy \le L \le 1\,Hy$ ; $5\,pF \le C \le 1\,\mu F$

2) PRACTICAL (P)

$0.2\,\mu Hy \le L \le 10\,Hy$ ; $2\,pF \le C \le 10\,\mu F$

3 MARGINAL (M)

$0.05\,\mu Hy \le L \le 100\,Hy$ ; $0.5\,pF \le C \le 500\,\mu F$

4) IMPRACTICAL (I) - ALL ELEMENTS EXCEEDING THE BOUNDS OF MARGINAL

$L < 0.05\,\mu Hy$ (50 nano Henry)

$L > 100\,Hy$

$C < 0.05\,pF$ ; $C > 500\,\mu F$

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

**Program Title** NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION FOR TYPES 1, 2, 6, AND 7

**Contributor's Name**

**Address**

**City** **State** **Zip Code**

**Program Description, Equations, Variables, etc.**

THE COLUMN HEADINGS ON FIGURE 2 ARE MEANT TO INDICATE RANGES OF ELEMENT VALUES. THE RANGES FOR THE FREQUENCY, THE LOADED Q AND THE IMPEDANCE LEVEL ARE

1) FREQUENCY

$f_0$ = 10 Hz MEANS: 3 Hz $\leq f_0 \leq$ 30 Hz
$f_0$ = 100 Hz MEANS: 30 Hz $\leq f_0 \leq$ 300 Hz
$f_0$ = 1 KHz MEANS: 300 Hz $\leq f_0 \leq$ 3 KHz
$f_0$ = 10 KHz MEANS: 3 KHz $\leq f_0 \leq$ 30 KHz
$f_0$ = 100 KHz MEANS: 30 KHz $\leq f_0 \leq$ 300 KHz
$f_0$ = 1 MHz MEANS: 300 KHz $\leq f_0 \leq$ 3 MHz
$f_0$ = 10 MHz MEANS: 3 MHz $\leq f_0 \leq$ 30 MHz
$f_0$ = 100 MHz MEANS: 30 MHz $\leq f_0 \leq$ 300 MHz

2 LOADED $Q_L$ FACTORS

$Q_L = 5$ MEANS: $3 \leq Q_L \leq 10$
$Q_L = 15$ MEANS: $10 \leq Q_L \leq 30$
$Q_L = 50$ MEANS: $30 \leq Q_L \leq 100$

3 IMPEDANCE LEVEL (SOURCE & LOAD RESISTANCES)

$R = 3\,\Omega$ MEANS: $1 \leq R \leq 10$ (POWER FILTERS)
$R = 50\,\Omega$ MEANS: $10 \leq R \leq 150$
$R = 500\,\Omega$ MEANS: $150 \leq R \leq 2.5K$
$R = 10K\,\Omega$ MEANS: $2.5K \leq R \leq 50K$

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

PHYSICAL REALIZABILITY OF A BAND-PASS FILTER

| Band-Pass Filter Prototype | $f_o$ = 1 kc | | | | | | | | | $f_o$ = 10 kc | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | |
| Type | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K |
| 1st | I | P | P | I | I | I | I | I | I | M | R | P | I | M | P | I | M | P |
| 2nd | I | P | P | I | I | I | I | I | I | M | R | P | I | M | I | I | M | P |
| 3rd | I | M | I | I | I | I | I | I | I | M | P | M | I | P | P | I | M | I |
| 4th | I | M | P | I | I | P | I | I | M | M | P | P | I | P | P | I | M | P |
| 5th | P | P | P | P | I | P | P | P | I | R | R | P | R | P | P | R | P | M |
| 6th | P | P | I | P | P | I | P | P | I | R | R | P | R | P | P | R | P | M |
| 7th | I | M | P | I | I | P | I | I | M | M | P | R | I | P | R | I | M | P |
| 8th | M | P | I | M | P | I | M | P | I | P | R | P | P | P | P | P | P | M |
| 9th | I | M | P | I | I | P | I | I | M | M | P | P | I | P | P | I | M | P |
| 10th | M | P | M | P | R | P | R | R | P | P | R | P | R | R | R | R | R | R |
| 11th | M | P | P | M | P | P | M | M | P | P | R | R | I | R | R | M | P | R |

Types 3, 4 and 5 are not included

| Band-Pass Filter Prototype | $f_o$ = 100 kc | | | | | | | | | $f_o$ = 1 mc | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | |
| Type | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K |
| 1st | P | R | R | P | P | I | M | M | I | P | R | P | P | P | I | M | P | I |
| 2nd | P | R | R | P | P | I | M | M | I | P | R | P | P | P | I | M | M | I |
| 3rd | P | R | P | P | R | P | M | P | P | R | R | P | R | R | R | M | P | I |
| 4th | P | R | R | P | R | R | M | P | R | R | R | R | P | R | R | M | P | R |
| 5th | R | R | P | R | R | P | R | R | P | R | R | P | R | R | M | R | P | I |
| 6th | R | R | P | R | R | P | R | P | P | R | R | P | R | R | M | R | P | I |
| 7th | P | R | R | P | R | R | M | P | R | R | R | R | P | R | R | M | P | R |
| 8th | R | R | P | R | R | P | R | R | P | R | R | P | R | R | M | R | P | I |
| 9th | P | R | R | P | R | R | M | P | R | R | R | R | P | R | R | M | P | R |
| 10th | R | R | R | R | R | P | R | R | P | R | R | P | R | R | M | R | R | M |
| 11th | R | R | R | R | R | R | P | R | R | R | R | R | R | R | R | R | R | R |

| Band-Pass Filter Prototype | $f_o$ = 10 mc | | | | | | | | | $f_o$ = 100 mc | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | |
| Type | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K |
| 1st | M | P | M | I | P | I | I | I | I | I | I | I | I | I | I | I | I | I |
| 2nd | M | P | M | I | P | I | I | I | I | I | I | I | I | I | I | I | I | I |
| 3rd | P | R | M | R | P | I | I | M | I | I | M | I | I | I | I | I | I | I |
| 4th | M | R | R | I | P | R | I | M | R | I | M | R | I | I | P | I | I | M |
| 5th | P | R | M | M | P | I | P | M | I | M | M | I | I | I | I | M | I | I |
| 6th | R | R | M | P | P | I | P | M | I | P | M | I | M | I | I | M | I | I |
| 7th | M | R | P | I | P | P | I | P | P | I | P | M | I | I | I | I | M | I |
| 8th | R | R | M | R | P | I | P | M | I | P | M | I | P | I | I | M | I | I |
| 9th | M | R | R | I | P | R | I | M | R | I | M | R | I | I | P | I | I | M |
| 10th | P | R | I | P | M | I | P | M | I | P | M | I | M | I | I | M | I | I |
| 11th | M | R | M | M | P | M | I | P | M | I | M | I | I | M | I | I | I | I |

Courtesy
Don White Consultants, Inc

FIGURE 2

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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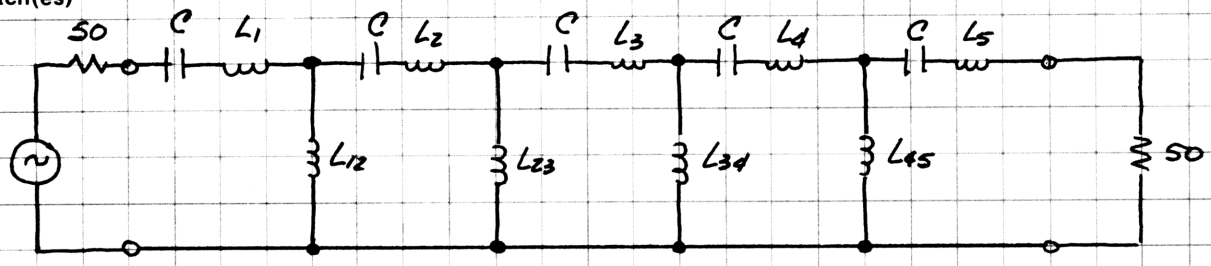
# Program Description II

**Sketch(es)**




TYPE 6 FILTER DESIGN EXAMPLE

**Sample Problem(s)** A MAXIMALLY FLAT PASSBAND (BUTTERWORTH) BANDPASS FILTER IS REQUIRED TO PASS A 500 HZ BAND OF FREQUENCIES THAT ARE CENTERED AT 10 KHZ. THE FILTER SHOULD REJECT FREQUENCIES REMOVED FROM 10 KHZ BY 500 HZ OR MORE (1000 HZ STOPBAND, $\lambda = 2$) BY AT LEAST 50 dB. THE BUTTERWORTH FILTER NOMOGRAPH SHOWS A $5^{th}$ ORDER FILTER IS REQUIRED.*

THE PROPER BANDPASS TOPOLOGY IS SELECTED FROM FIGURE 2 UNDER THE HEADINGS $f_0 = 10$ KHZ, $Q_L = 10^4/500 = 20$ (USE $Q_L = 15$ COLUMN), AND $R = 50$ TO FIND THAT TYPE 6 IS READILY REALIZABLE, THEREFORE, A TYPE 6 FILTER WILL BE DESIGNED

**Solution(s)**

1) LOAD THE NORMALIZED LOWPASS COEFFICIENT PROGRAM AND OBTAIN THE $5^{th}$ ORDER BUTTERWORTH COEFFICIENTS (THEY ARE STORED AUTOMATICALLY)
2) LOAD THIS PROGRAM
3) KEY IN CENTER FREQ. [EEX] [4] [A]
4) KEY IN BANDWIDTH [5] [0] [0] [B]
5) KEY IN RESISTANCE [5] [0] [C]
6) SELECT TYPE 6 [f] [c]
7) PRINTER WILL PRINT ELEMENT VALUES AND STOP.

**Reference(s)**

* SEE LOWPASS COEFFICIENT PROGRAM FOR NOMOGRAPHS

DONALD R. J. WHITE, "A HANDBOOK ON ELECTRICAL FILTERS" PUB. DON WHITE CONSULTANTS, GERMANTOWN MD

ANATOL ZVEREV, "A HANDBOOK OF FILTER SYNTHESIS" WILEY, 1967

# Program Description II

LOAD NORMALIZED LOWPASS COEFFICIENT PROGRAM

```
n =     5.000000 GSBA
Butterworth coef. GSBa

a1      0.618034  ***
a2      1.618034  ***
a3      2.000000  ***
a4      1.618034  ***
a5      0.618034  ***
```

PRINTER OUTPUT FOR SAMPLE PROBLEM

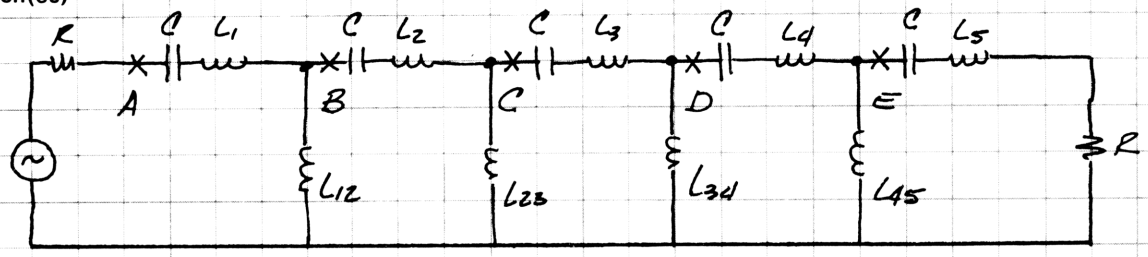
LOAD THIS PROGRAM

```
fo =    1.+04 GSBA
BW =     500. GSBB
R =       50. GSBC
type 6 ——— GSBc

TYPE    6.

C       25.75-09  ***
L1      9.345-03  ***

L12     491.8-06  ***

C       25.75-09  ***
L2      9.071-03  ***

L23     273.4-06  ***

C       25.75-09  ***
L3      9.290-03  ***

L34     273.4-06  ***

C       25.75-09  ***
L4      9.071-03  ***

L45     491.8-06  ***

C       25.75-09  ***
L5      9.345-03  ***
```

**Reference(s)**

# Program Description II

**Sketch(es)**




TYPE 6 TUNING TECHNIQUE

**Sample Problem(s)** AFTER THE FILTER IS DESIGNED AND THE INDUCTORS AND CAPACITORS OBTAINED, THE FILTER MUST BE TUNED. FOR SERIES RESONANT TANKS, SUCH AS IN THIS FILTER AND IN TYPES 8 AND 10, TUNING IS ACCOMPLISHED BY DECOUPLING INDIVIDUAL TANKS THROUGH OPENING UP ADJACENT RESONANT CIRCUITS.

ASSUME THE INDUCTORS ARE WOUND ON FERRITE POT CORES AND ARE THE ADJUSTABLE ELEMENT. TO TUNE C & $L_1$ TEMPORARILY OPEN THE FILTER AT "B" AND TUNE $L_1$ TO RESONANCE AT $f_0$ = 10000 Hz IN THIS EXAMPLE.

TO TUNE $L_2$, RE-ESTABLISH THE CONNECTION AT "B" AND TEMPORARILY OPEN THE CIRCUIT AT POINTS "A" AND "C" AND TUNE $L_2$ TO RESONANCE AT $f_0$ = 10000 Hz.

CONTINUE THIS TEMPORARY CIRCUIT OPENING PROCEDURE UNTIL ALL L'S WITH ADJACENT COUPLING CIRCUITS HAVE BEEN TUNED TO RESONANCE.

THIS WHOLE PROCEDURE IS CONTINGENT UPON THE INDIVIDUAL ELEMENTS HAVING ALREADY BEEN TRIMMED TO THE DESIGN VALUES (± 1% OR BETTER) BEFORE THE FILTER WAS ASSEMBLED.

**Reference(s)** SEE FERROXCUBE CATALOG "LINEAR FERRITE MATERIALS AND COMPONENTS" FOR DETAILS ON THE INDUCTOR DESIGN

SEE EXAMPLE IN TYPES 8, 9, 10, & 11 PROGRAM FOR PARALLEL TANK TUNING METHODS

# User Instructions

| Type 1 | Type 2 | Type 6 | Type 7 | All Types |
|---|---|---|---|---|
| $f_{center}$ | Bandwidth | Resistance | | |

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | OUTPUT DATA/UNITS |
|---|---|---|---|---|
| 1 | LOAD BOTH SIDES OF PROGRAM CARD | | | |
| 2 | KEY IN CENTER FREQUENCY IN HZ | $f_0$ | A | |
| 3 | KEY IN BANDWIDTH IN HERTZ | BW | B | |
| 4 | KEY IN TERMINATION RESISTANCE IN OHMS | R | C | |
| 5 | SELECT TYPE OF FILTER DESIRED | | | |
| | TYPE 1 | | f A | $C_1, L_1$<br>$C_2, L_2$<br>⋮<br>$C_n, L_n$ |
| | TYPE 2 | | f B | $C_1, L_1$<br>$C_2, L_2$<br>⋮<br>$C_n, L_n$ |
| | TYPE 6 | | f C | $C_1, L_1$<br>$L_{12}$<br>$C_2, L_2$<br>$L_{23}$<br>⋮<br>$C_3, L_n$ |
| | TYPE 7 | | f D | $C_1, L$<br>$C_{12}$<br>$C_2, L$<br>$C_{23}$<br>⋮<br>$C_n, L$ |
| | ALL TYPES IN SUCCESSION | | f E | |

# 97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | #LBLA | 21 11 | enter f center |
| 002 | Pi | 16-24 | Calculate 2πfo |
| 003 | 2 | 02 | & store in Ro |
| 004 | × | -35 | |
| 005 | × | -35 | |
| 006 | STO0 | 35 00 | |
| 007 | RTN | 24 | |
| 008 | #LBLB | 21 12 | Enter Bandwidth |
| 009 | Pi | 16-24 | Calculate $Q_L = \frac{2\pi f_o}{2\pi BW}$ |
| 010 | × | -35 | |
| 011 | 2 | 02 | and store in $R_1$ |
| 012 | × | -35 | |
| 013 | RCL0 | 36 00 | |
| 014 | ÷ | -24 | |
| 015 | 1/X | 52 | |
| 016 | STO1 | 35 01 | |
| 017 | RTN | 24 | |
| 018 | #LBLC | 21 13 | Enter resistance |
| 019 | STO2 | 35 02 | and store in $R_2$ |
| 020 | RTN | 24 | |
| 021 | #LBLe | 21 16 15 | calculate element |
| 022 | GSBa | 23 16 11 | values for del types |
| 023 | GSBb | 23 16 12 | (1, 2, 6 & 7) |
| 024 | GSBc | 23 16 13 | |
| 025 | GSBd | 23 16 14 | |
| 026 | RTN | 24 | |
| 027 | #LBLa | 21 16 11 | Type 1 routine |
| 028 | SPC | 16-11 | print heading |
| 029 | 1 | 01 | |
| 030 | PRTX | -14 | |
| 031 | SPC | 16-11 | |
| 032 | SF1 | 16 21 01 | set type 1 printing order |
| 033 | GTO0 | 22 00 | |
| 034 | #LBLb | 21 16 12 | Type 2 routine |
| 035 | SPC | 16-11 | print heading |
| 036 | 2 | 02 | |
| 037 | PRTX | -14 | |
| 038 | SPC | 16-11 | |
| 039 | CF1 | 16 22 01 | set type 2 printing order |
| 040 | #LBL0 | 21 00 | |
| 041 | RCL1 | 36 01 | Q |
| 042 | RCL2 | 36 02 | R |
| 043 | ÷ | -24 | |
| 044 | RCL0 | 36 00 | $\omega_o$ |
| 045 | ÷ | -24 | |
| 046 | STO4 | 35 04 | $Q_L/(R\omega_o)$ |
| 047 | RCL2 | 36 02 | R |
| 048 | X² | 53 | $R^2$ |
| 049 | × | -35 | |
| 050 | STO5 | 35 05 | $Q_L R/\omega_o$ |
| 051 | 0 | 00 | initialize k |
| 052 | STO7 | 35 07 | |
| 053 | #LBL1 | 21 01 | |
| 054 | GSB9 | 23 09 | increment k |
| 055 | X≥Y? | 16-35 | test for loop exit |
| 056 | RTN | 24 | |
| 057 | RCL1 | 36 45 | Recall $g_k$ |
| 058 | RCL4 | 36 04 | Recall $Q/(R\omega_o)$ |
| 059 | SF0 | 16 21 00 | print $Q g_k/(R\omega_o)$ first |
| 060 | F1? | 16 23 01 | test for type 1 printing order |
| 061 | GTO6 | 22 06 | |
| 062 | CLX | -51 | setup type 2 |
| 063 | RCL5 | 36 05 | printing order |
| 064 | CF0 | 16 22 00 | |
| 065 | #LBL6 | 21 06 | |
| 066 | GSB8 | 23 08 | Calculate & print LC values |
| 067 | GSB9 | 23 09 | increment k |
| 068 | X≥Y? | 16-35 | test for loop exit |
| 069 | RTN | 24 | |
| 070 | RCL1 | 36 45 | Recall $g_k$ |
| 071 | RCL5 | 36 05 | Recall $Q_L R/\omega_o$ |
| 072 | CF0 | 16 22 00 | print $g_k Q_L R/\omega_o$ last |
| 073 | F1? | 16 23 01 | test for type 1 printing order |
| 074 | GTO6 | 22 06 | |
| 075 | CLX | -51 | setup type 2 |
| 076 | RCL4 | 36 04 | printing order |
| 077 | SF0 | 16 21 00 | |
| 078 | #LBL6 | 21 06 | |
| 079 | GSB8 | 23 08 | Calculate & Print LC values |
| 080 | GTO1 | 22 01 | Goto loop start |
| 081 | #LBLc | 21 16 13 | Type 6 routine |
| 082 | SPC | 16-11 | print heading |
| 083 | 6 | 06 | |
| 084 | PRTX | -14 | |
| 085 | GSB5 | 23 05 | Calculate type 7 constants |
| 086 | RCL2 | 36 02 | Change to type 6 |
| 087 | X² | 53 | constants |
| 088 | STX4 | 35-35 04 | |
| 089 | ST÷5 | 35-24 05 | |
| 090 | CF0 | 16 22 00 | not the last tank ckt. |
| 091 | CF1 | 16 22 01 | print common elt. first (C) |
| 092 | GTO2 | 22 02 | |
| 093 | #LBLd | 21 16 14 | Type 7 routine |
| 094 | SPC | 16-11 | print heading |
| 095 | 7 | 07 | |
| 096 | PRTX | -14 | |
| 097 | SPC | 16-11 | |
| 098 | GSB5 | 23 05 | Calculate type 7 constants |
| 099 | CF0 | 16 22 00 | print common elt last (L) |
| 100 | SF1 | 16 21 01 | |
| 101 | #LBL2 | 21 02 | |
| 102 | GSB9 | 23 09 | increment k |
| 103 | X≥Y? | 16-35 | test for loop exit |
| 104 | GTO6 | 22 06 | |
| 105 | GSB4 | 23 04 | Calculate & Print LC values |
| 106 | GTO2 | 22 02 | |
| 107 | #LBL6 | 21 06 | last element |
| 108 | SF0 | 16 21 00 | |
| 109 | GSB4 | 23 04 | calculate element values. |
| 110 | SPC | 16-11 | routine exit |
| 111 | RTN | 24 | |
| 112 | #LBL4 | 21 04 | Calculate type 6 & 7 values |

## REGISTERS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 $2\pi f_c$ | 1 $Q_L$ | 2 $R$ | 3 | 4 used | 5 used | 6 $n$ | 7 $k$ | 8 $(a_{k-1}\cdot a_k)^{-1/2}$ | 9 $(a_k\cdot a_{k+1})^{-1/2}$ |
| S0 $a_n$ | S1 $a_{n-1}$ | S2 $a_{n-2}$ | S3 $a_{n-3}$ | S4 $a_{n-4}$ | S5 $a_{n-5}$ | S6 $a_{n-6}$ | S7 $a_{n-7}$ | S8 $a_{n-8}$ | S9 $a_{n-9}$ |
| A $a_{n-10}$ | B $a_{n-11}$ | C $a_{n-12}$ | D $(-1)^k$ | E $a_{k+1}$ | I Index | | | | |

# 97 Program Listing II



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 113 | F1? | 16 23 01 | print common elt last ? for type 6 ? |
| 114 | GTO6 | 22 06 | recall common element and print (C) |
| 115 | RCL5 | 36 05 | |
| 116 | PRTX | -14 | |
| 117 | #LBL6 | 21 06 | |
| 118 | F0? | 16 23 00 | last tank ? |
| 119 | GTO6 | 22 06 | |
| 120 | RCL1 | 36 45 | recall $g_{k+1}$ |
| 121 | RCLE | 36 15 | recall $g_k$ |
| 122 | X⇄Y | -41 | |
| 123 | STOE | 35 15 | Store $g_{k+1}$ |
| 124 | × | -35 | |
| 125 | 1/X | 52 | |
| 126 | √X | 54 | |
| 127 | STO9 | 35 09 | $(a_k \cdot a_{k+1})^{-1/2}$ |
| 128 | #LBL6 | 21 06 | |
| 129 | F0? | 16 23 00 | last tank ? |
| 130 | 0 | 00 | |
| 131 | RCL1 | 36 01 | Q |
| 132 | X⇄Y | -41 | |
| 133 | - | -45 | |
| 134 | RCL8 | 36 08 | $(a_{k-1} \cdot a_k)^{-1/2}$ |
| 135 | - | -45 | |
| 136 | RCL4 | 36 04 | type 6 $1/(a_1 R Q_L w_0)$ type 7 $R/a_1 Q_L w_0$ |
| 137 | × | -35 | |
| 138 | PRTX | -14 | print tank element value |
| 139 | RCL5 | 36 05 | recall common L or C |
| 140 | F1? | 16 23 01 | type 7 filter ? |
| 141 | PRTX | -14 | print common L |
| 142 | SPC | 16-11 | |
| 143 | F0? | 16 23 00 | last tank ? |
| 144 | RTN | 24 | |
| 145 | RCL9 | 36 09 | calculate & print coupling element |
| 146 | RCL4 | 36 04 | |
| 147 | × | -35 | |
| 148 | PRTX | -14 | |
| 149 | SPC | 16-11 | |
| 150 | RCL9 | 36 09 | $(a_{k+1} \cdot a_k)^{-1/2}$ becomes |
| 151 | STO8 | 35 08 | $(a_{k-1} \cdot a_k)^{-1/2}$ |
| 152 | RTN | 24 | |
| 153 | #LBL5 | 21 05 | Type 6 & 7 loop initialization |
| 154 | 0 | 00 | initialize k |
| 155 | STO7 | 35 07 | |
| 156 | SPC | 16-11 | |
| 157 | GSB9 | 23 09 | increment k = 1 |
| 158 | RCL1 | 36 45 | recall $a_1$ |
| 159 | STOE | 35 15 | store $a_1$ |
| 160 | RCL2 | 36 02 | recall R |
| 161 | ÷ | -24 | |
| 162 | RCL0 | 36 00 | recall $w_0$ |
| 163 | ÷ | -24 | |
| 164 | STO4 | 35 04 | $a_1/R w_c$ |
| 165 | RCL2 | 36 02 | R |
| 166 | RCLE | 36 15 | $a_1$ |
| 167 | ÷ | -24 | |
| 168 | RCL0 | 36 00 | $w_0$ |
| 169 | ÷ | -24 | |
| 170 | RCL1 | 36 01 | $Q_L$ |
| 171 | ÷ | -24 | |
| 172 | STO5 | 35 05 | $R/a_1 Q_L w_0$ |
| 173 | 0 | 00 | |
| 174 | STO8 | 35 08 | $(a_1 \cdot a_0)^{-1/2} = 0$ |
| 175 | RTN | 24 | |
| 176 | #LBL8 | 21 08 | Type 1 & 2 output routine |
| 177 | × | -35 | scale low pass element |
| 178 | STO8 | 35 08 | |
| 179 | F0? | 16 23 00 | print here ? |
| 180 | PRTX | -14 | |
| 181 | RCL0 | 36 00 | calculate and print mating resonant element |
| 182 | X² | 53 | |
| 183 | × | -35 | |
| 184 | 1/X | 52 | |
| 185 | PRTX | -14 | |
| 186 | F0? | 16 23 00 | test for further printing |
| 187 | GTO6 | 22 06 | |
| 188 | RCL8 | 36 08 | |
| 189 | PRTX | -14 | |
| 190 | #LBL6 | 21 06 | |
| 191 | SPC | 16-11 | |
| 192 | RTN | 24 | |
| 193 | #LBL9 | 21 09 | increment k routine |
| 194 | 1 | 01 | increments k |
| 195 | ST+7 | 35-55 07 | |
| 196 | RCL7 | 36 07 | setup I register |
| 197 | 9 | 09 | |
| 198 | + | -55 | |
| 199 | STOI | 35 46 | |
| 200 | RCL7 | 36 07 | recall variables to test for loop exit. |
| 201 | RCL6 | 36 06 | |
| 202 | 1 | 01 | |
| 203 | + | -55 | |
| 204 | RTN | 24 | |

## LABELS

| | | | | |
|---|---|---|---|---|
| A STORE $w_0 = 2\pi f_0$ | B enter BW Calculate $Q_L$ | C enter & store resistance | D not used | E not used |
| a Type 1 Start | b Type 2 Start | c type 6 Start | d Type 7 Start | e do all types |
| 0 Type 1 loop return | 1 Type 1 & 2 loop return | 2 Type 6 & 7 loop return | 3 not used | 4 Type 6 & 7 loop element values |
| 5 Type 6 & 7 loop initialization | 6 local loop label | 7 not used | 8 Type 1 & 2 output routine | 9 increment k |

## FLAGS

| | |
|---|---|
| 0 | last tank cut |
| 1 | element printing order |
| 2 | not used |
| 3 | not used. |

## SET STATUS

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

# Program Description I

**Program Title** NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION FOR TYPES 8, 9, 10, & 11

**Contributor's Name** BRUCE K MURDOCK

**Address** 6875 SABADO TARDE RD

**City** GOLETA **State** CALIF **Zip Code** 93017

**Program Description, Equations, Variables** THIS PROGRAM CONVERTS THE NORMALIZED LOWPASS COEFFICIENTS (1 OHM, 1 RADIAN/SEC) TO ANY OR ALL OF FOUR BANDPASS FILTER TOPOLOGIES THIS PROGRAM IS ONE OF A SET OF TRANSFORMATION PROGRAMS.

FIGURE 1 SHOWS THE FOUR BANDPASS TOPOLOGIES DIFFERENT TOPOLOGIES ARE PROVIDED SO THAT A MIX OF COMPONENT VALUES ARE OBTAINED. FOR A GIVEN CENTER FREQUENCY, BANDWIDTH, AND TERMINATION IMPEDANCE LEVEL, SOME TOPOLOGIES WILL HAVE MORE PHYSICALLY REALIZABLE COMPONENT VALUES THAN OTHERS.

TABLE 7.2 FROM WHITE HAS BEEN REPRODUCED AS A GUIDE AS TO THE MOST REALIZABLE BANDPASS TOPOLOGY FOR A GIVEN APPLICATION. THIS REPRODUCTION IS SHOWN IN FIGURE 2.

**Operating Limits and Warnings** THIS PROGRAM OBTAINS THE LOWPASS NORMALIZED ELEMENT VALUES FROM REGISTER STORAGE IN THE SECONDARY SET OF REGISTERS. n, THE FILTER ORDER IS ALSO STORED. ONE SHOULD RUN THE NORMALIZED LOWPASS COEFFICIENT PROGRAM FIRST, OR MANUALLY PLACE THE DESIRED NORMALIZED COEFFICIENTS AND FILTER ORDER IN STORAGE BEFORE RUNNING THIS PROGRAM.

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I


Program Title NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATIONS FOR TYPES 8, 9, 10, 11

Contributor's Name BRUCE K. MURDOCK

Address 6875 SABADO TARDE RD

City GOLETA State CALIF Zip Code 93017


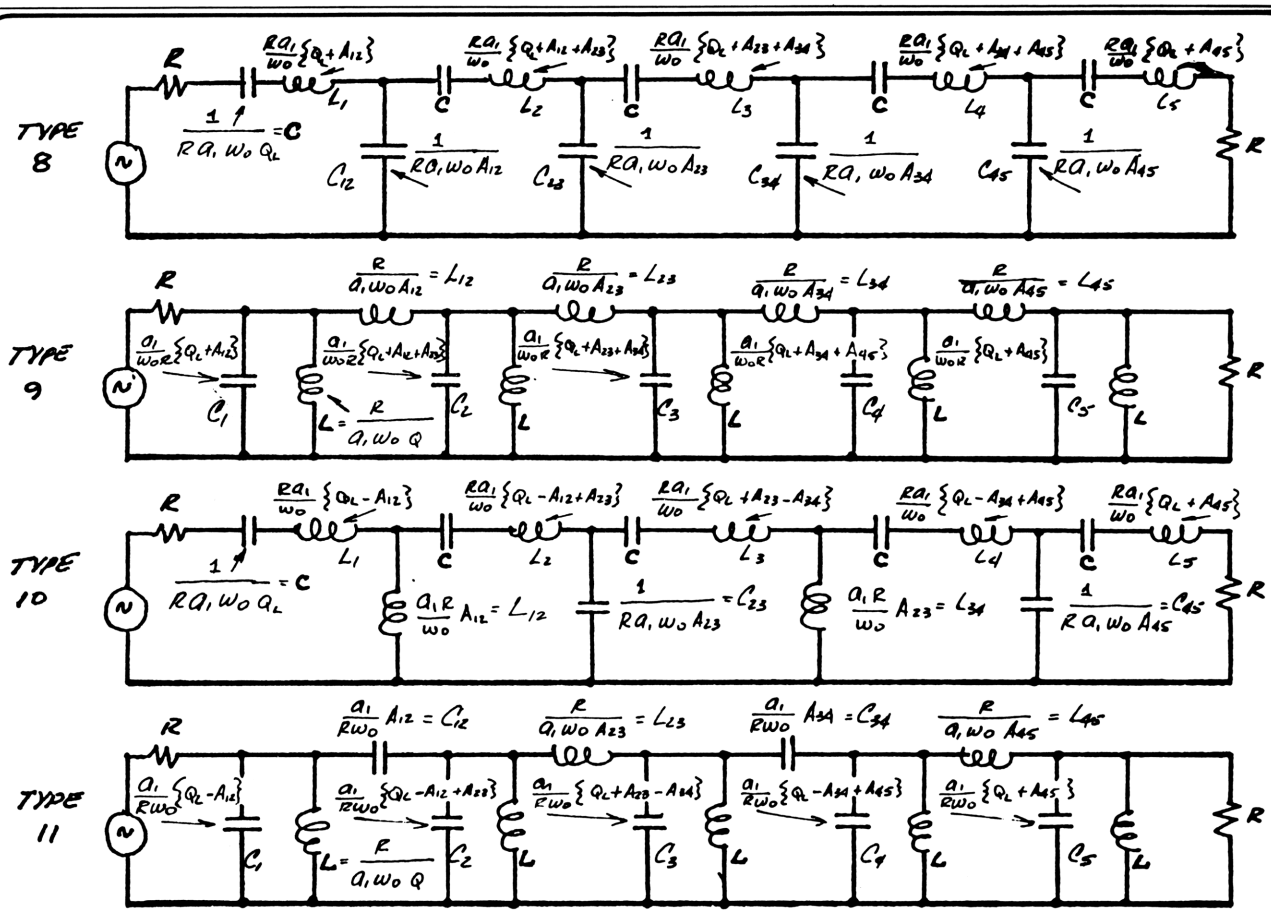


FIGURE 1, BANDPASS TOPOLOGIES

$$Q_L = f_0/BW \quad ; \quad a_k \equiv g_k \quad ; \quad A_{ij} = (a_i \cdot a_j)^{-1/2}$$

THE FILTER MUST HAVE EQUAL TERMINATION IMPEDANCES FOR THESE ROUTINES, HENCE, IF CHEBYCHEV RESPONSE IS DESIRED, THE FILTER ORDER MUST BE ODD. EVEN ORDER CHEBYCHEV FILTERS HAVE UNEQUAL TERMINATION IMPEDANCES

# Program Description I

THE LOWPASS NORMALIZED COEFFICIENTS MAY BE TRANSFORMED TO AN INFINITE VARIETY OF BANDPASS TOPOLOGIES. THE REASON FOR NEEDING MORE THAN ONE TRANSFORMATION IS PHYSICAL REALIZABILITY. FOR EXAMPLE, ONE WOULD NOT WANT TO END UP WITH A BANDPASS STRUCTURE CONTAINING 1 μF CAPACITORS WHEN THE OPERATING FREQUENCY IS 100 MEGAHERTZ.

O.R.J. WHITE HAS AUTHORED AN EXCELLENT FILTER DESIGN BOOK WHICH IS VERY PRACTICAL IN NATURE. ONE PROBLEM HE ADDRESSES, IN DETAIL, IS THIS PHYSICAL REALIZABILITY PROBLEM FOR BANDPASS, LOWPASS, AND HIGHPASS FILTERS. HE HAS DERIVED ELEVEN DIFFERENT BANDPASS TOPOLOGIES TO ALLOW FINDING A MIX OF COMPONENT VALUES THAT ARE REALIZABLE.

THE FOLLOWING FOUR DEFINATIONS OF ELEMENT PHYSICAL REALIZABILITY ARE ESTABLISHED:

1) READILY REALIZABLE (R)
   $1\,\mu Hy \le L \le 1\,Hy$ ; $5pF \le C \le 1\mu F$

2) PRACTICAL (P)
   $0.2\,\mu Hy \le L \le 10\,Hy$ ; $2pF \le C \le 10\mu F$

3 MARGINAL (M)
   $0.05\,\mu Hy \le L \le 100\,Hy$ ; $0.5\,pF \le C \le 500\,\mu F$

4) IMPRACTICAL (I) - ALL ELEMENTS EXCEEDING THE BOUNDS OF MARGINAL
   $L < 0.05\,\mu Hy$ (50 nano Henry)
   $L > 100\,Hy$
   $C < 0.05\,pF$ ; $C > 500\,\mu F$

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# Program Description I

**Program Title** NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION FOR TYPES 8,9,10, AND 11

**Contributor's Name**

**Address**

**City** **State** **Zip Code**

**Program Description, Equations, Variables** THE COLUMN HEADINGS ON FIGURE 2 ARE MEANT TO INDICATE RANGES OF ELEMENT VALUES. THESE RANGES FOR FREQUENCY, LOADED Q, AND IMPEDANCE LEVEL ARE DEFINED AS FOLLOWS

1) FREQUENCY

| | | |
|---|---|---|
| $f_0 = 10$ Hz | IMPLIES | $3\text{Hz} \le f_0 \le 30\text{Hz}$ |
| $f_0 = 100$ Hz | " | $30\text{Hz} \le f_0 \le 300$ Hz |
| $f_0 = 1$ KHz | " | $300\text{Hz} \le f_0 \le 3$ KHz |
| $f_0 = 10$ KHz | " | $3\text{KHz} \le f_0 \le 30$ KHz |
| $f_0 = 100$ KHz | " | $30\text{KHz} \le f_0 \le 300$ KHz |
| $f_0 = 1$ MHz | " | $300\text{KHz} \le f_0 \le 3$ MHz |
| $f_0 = 10$ MHz | " | $3\text{MHz} \le f_0 \le 30$ MHz |
| $f_0 = 100$ MHz | " | $30\text{MHz} \le f_0 \le 300$ MHz |

2) LOADED $Q_L$ ; $Q_L = f_0/BW$

| | | |
|---|---|---|
| $Q_L = 5$ | IMPLIES | $3 \le Q_L \le 10$ |
| $Q_L = 15$ | " | $10 \le Q_L \le 30$ |
| $Q_L = 50$ | " | $30 \le Q_L \le 100$ |

3) IMPEDANCE LEVEL (SOURCE & LOAD RESISTANCES)

| | | |
|---|---|---|
| $R = 50$ OHMS | IMPLIES | $10 \le R \le 150$ |
| $R = 500$ OHMS | " | $150 \le R \le 2.5$K |
| $R = 10$K OHMS | " | $2.5\text{K} \le R \le 50$K |

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# Program Description I

PHYSICAL REALIZABILITY OF A BAND-PASS FILTER

| Band-Pass Filter Prototype | $f_o$ = 1 kc | | | | | | | | | $f_o$ = 10 kc | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | |
| Type | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K |
| 1st | I | P | P | I | I | I | I | I | I | M | R | P | I | M | P | I | M | P |
| 2nd | I | P | P | I | I | I | I | I | I | M | R | P | I | M | I | I | M | P |
| 3rd | I | M | I | I | I | I | I | I | I | M | P | M | I | P | P | I | M | I |
| 4th | I | P | P | I | I | P | I | I | M | M | P | P | I | P | P | I | M | P |
| 5th | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P |
| 6th | P | P | I | P | P | I | P | P | I | R | R | P | R | P | P | R | P | M |
| 7th | I | M | P | I | I | P | I | I | M | M | P | R | I | P | R | I | M | P |
| 8th | M | P | I | M | P | I | M | P | I | P | R | P | P | P | P | P | P | M |
| 9th | I | M | P | I | I | P | I | I | M | M | P | P | I | P | P | I | M | P |
| 10th | M | P | M | P | R | P | R | R | P | P | R | P | R | R | R | R | R | R |
| 11th | M | P | P | M | P | P | M | M | P | P | R | R | I | R | R | M | P | R |

Types 3, 4, and 5 are not included.

| Band-Pass Filter Prototype | $f_o$ = 100 kc | | | | | | | | | $f_o$ = 1 mc | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | |
| Type | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K |
| 1st | P | R | R | P | P | I | M | M | I | P | R | P | P | P | I | M | P | I |
| 2nd | P | R | R | P | P | I | M | M | I | P | R | P | P | P | I | M | M | I |
| 3rd | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P |
| 4th | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P |
| 5th | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P |
| 6th | R | R | P | R | R | P | R | P | P | R | R | P | R | R | M | R | P | I |
| 7th | P | R | R | P | R | R | M | P | R | R | R | R | P | R | R | M | P | R |
| 8th | R | R | P | R | R | P | R | R | P | R | R | P | R | R | M | R | P | I |
| 9th | P | R | R | P | R | R | M | P | R | R | R | R | P | R | R | M | P | R |
| 10th | R | R | R | R | R | P | R | R | P | R | R | P | R | R | M | R | R | M |
| 11th | R | R | R | R | R | R | P | R | R | R | R | R | R | R | R | R | R | R |

| Band-Pass Filter Prototype | $f_o$ = 10 mc | | | | | | | | | $f_o$ = 100 mc | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | | $Q_L$ = 5 | | | $Q_L$ = 15 | | | $Q_L$ = 50 | | |
| Type | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K | 50 | 500 | 10K |
| 1st | M | P | M | I | P | I | I | I | I | I | I | I | I | I | I | I | I | I |
| 2nd | M | P | M | I | P | I | I | I | I | I | I | I | I | I | I | I | I | I |
| 3rd | P | P | M | P | P | I | P | M | I | P | M | I | P | P | P | P | P | I |
| 4th | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P |
| 5th | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P | P |
| 6th | R | R | M | P | P | I | P | M | I | P | M | I | M | I | I | M | I | I |
| 7th | M | R | P | I | P | P | I | P | P | I | P | M | I | I | I | I | M | I |
| 8th | R | R | M | R | P | I | P | M | I | P | M | I | P | I | I | M | I | I |
| 9th | M | R | R | I | P | R | I | M | R | I | M | R | I | I | P | I | I | M |
| 10th | P | R | I | P | M | I | P | M | I | P | M | I | M | I | I | M | I | I |
| 11th | M | R | M | M | P | M | I | P | M | I | M | I | I | M | I | I | I | I |

FIGURE 2

Courtesy:
Don White Consultants, Inc.

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# Program Description I

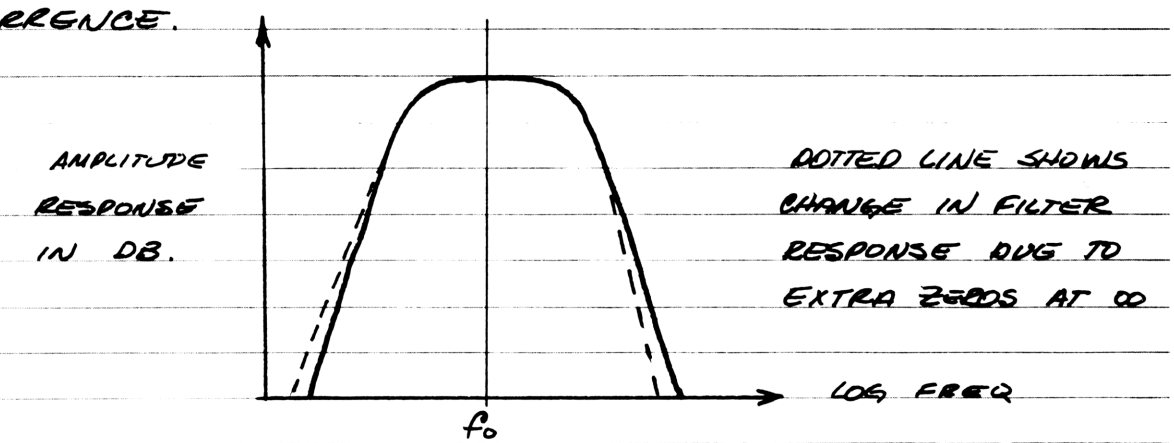
**Program Title** NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION FOR TYPES 8, 9, 10, & 11

**Contributor's Name**

**Address**

**City** **State** **Zip Code**

**Program Description, Equations, Variables** OF THE FILTER TYPES PRESENTED HERE, TYPES 1, 2, 6, 7, 8, 9, 10, & 11, ONLY TYPES 1 & 2 ARE AN EXACT BANDPASS TRANSFORMATION OF THE LOWPASS CHARACTERISTICS. ALL THE OTHER TYPES ARE NARROWBAND APPROXIMATIONS I.E. THEY WILL FAITHFULLY TRANSFORM THE PASSBAND CHARACTERISTICS OF THE LOWPASS AND THE STOPBAND WITHIN A FEW OCTAVES OF THE PASSBAND. TYPES 6, 7, 8, AND 9 DO NOT HAVE EQUAL NUMBERS OF ZEROS OF TRANSMISSION AT ZERO FREQUENCY AND AT INFINITE FREQUENCY. TYPES 1 AND 2 DO HAVE THIS TRANSMISSION ZERO BALANCE WHICH IS REQUIRED FOR THE EXACT TRANSFORMATION. THE RESULT OF THE IMBALANCE OF ZEROS OF TRANSMISSION IN TYPES 6, 7, 8, AND 9 IS TO SKEW THE FILTER RESPONSE AWAY FROM THE FREQUENCY WHERE THE PLURALITY OF ZEROS EXISTS. FIGURE 3 REPRESENTS THIS OCCURRENCE.

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# Program Description I

**Program Title** NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION FOR TYPES 8, 9, 10, AND 11

**Contributor's Name**

**Address**

**City** **State** **Zip Code**

THIS SKEWING OF THE RESPONSE DOES NOT OCCUR WITH TYPES 10 AND 11 BECAUSE THE COUPLING ELEMENTS ARE ALTERNATED THROUGH THE FILTER STRUCTURE I.E. A CAPACITOR IN SERIES GIVES A ZERO OF TRANSMISSION AT D.C. AS DOES AN INDUCTOR IN SHUNT. LIKEWISE A INDUCTOR IN SERIES OR CAPACITOR IN SHUNT CAN PROVIDE A ZERO OF TRANSMISSION AT INFINITE FREQUENCY.

ONE SHOULD NOT CHOOSE TYPES 10 OR 11 AUTOMATICALLY AS THESE FILTERS CONTAIN REDUNDANT INDUCTORS AS DO TYPES 6 AND 9. FOR A GIVEN FILTER REQUIREMENT, ONE SHOULD CONSULT FIGURE 2 TO DETERMINE WHAT TYPES ARE MOST EASILY REALIZED, AND THEN PERFORM A TRADEOFF BETWEEN FILTER ORDER AND FILTER TYPE TO DETERMINE THE SIMPLEST OVERALL FILTER DESIGN I.E. AT FREQUENCIES BETWEEN 1KHZ AND 100 KHZ, A DESIGN WITH THE MINIMUM NUMBER OF INDUCTORS IS USUALLY MOST DESIREABLE AT FREQUENCIES ABOVE 1MHZ, TUNING MAY BE MORE DIFFICULT AND THE SIMPLEST TOPOLOGY IS SOUGHT. BELOW 1KHZ, THE FILTER IS USUALLY AN ACTIVE DESIGN WHICH IS THE SUBJECT OF A DIFFERENT SET OF FILTER DESIGN PROGRAMS.

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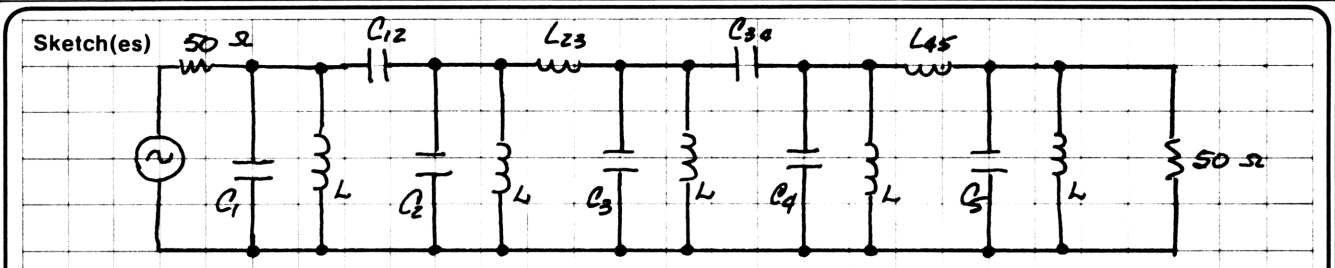
# Program Description II

**Sketch(es)**




TYPE 11 EXAMPLE

**Sample Problem(s)** A CHEBYCHEV BANDPASS FILTER IS NEEDED TO PASS A 20KHZ BAND OF INFORMATION AT 1 MHZ WITH .5 dB RIPPLE OR LESS AND TO OPERATE IN A 50 OHM SYSTEM. AT 30 KHZ REMOVED FROM 1 MHZ, THE FILTER RESPONSE SHOULD BE DOWN AT LEAST 60 dB. THE CHEBYCHEV FILTER NOMOGRAPH* SHOWS A FILTER ORDER OF 5 IS REQUIRED. FIGURE 2 UNDER THE HEADINGS OF $f_0 = 1\,MHz$, $Q_L = 10^6/2\times10^4 = 50$, $R = 50$ SHOWS TYPES 8, 10, OR 11 TO BE READILY REALIZABLE. TYPE 11 WILL BE CHOSEN SINCE THIS TOPOLOGY HAS THE MAXIMUM NUMBER OF INDUCTORS GROUNDED.

**Solution(s)**

1) LOAD THE NORMALIZED LOWPASS PROGRAM AND OBTAIN THE 5th ORDER, .5 dB CHEBYCHEV COEFFICIENTS
2) LOAD THIS PROGRAM
3) KEY IN CENTER FREQ. [EEX] [6] [A]
4) KEY IN BANDWIDTH [2] [EEX] [4] [B]
5) KEY IN RESISTANCE [5] [0] [C]
6) SELECT TYPE 11 [f] [D]
7) PRINTER WILL PRINT ELEMENT VALUES AND STOP

**Reference(s)** * SEE LOWPASS COEFFICIENT PROGRAM FOR NOMOGRAPHS

# Program Description II

**Sketch(es)** HP-97 PRINTER OUTPUT FOR SAMPLE PROGRAM

LOAD LOWPASS COEFFICIENT PROGRAM

```
n =    5.000000 GSBA
εdB =   .500000 GSBB
       1.059259  *** = ω-3dB

       1.705770  *** = g1
       1.229627  *** = g2
       2.540827  *** = g3
       1.229627  *** = g4
       1.705770  *** = g5
```

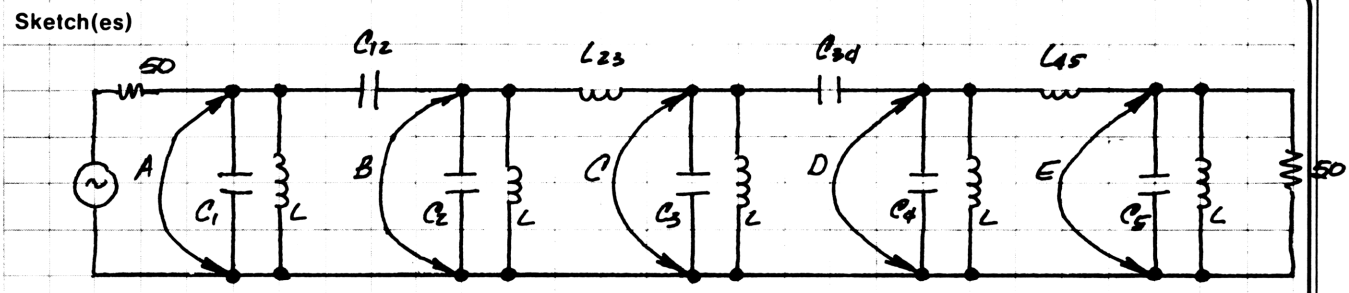
LOAD BANDPASS PROGRAM

```
fo =   1.+06 GSBA
BW =   2.+04 GSBB
R  =     50. GSBC
CALCULATE TYPE 11 GSBd

TYPE 11.

C1   267.7-09  ***
L    93.30-09  ***

C12  3.749-09  ***

C2   270.8-09  ***
L    93.30-09  ***

L23  8.246-06  ***

C3   271.5-09  ***
L    93.30-09  ***

C34  3.072-09  ***

C4   272.2-09  ***
L    93.30-09  ***

C45  6.756-06  ***

C5   275.2-09  ***
L    93.30-09  ***
```

**Reference(s)**

# Program Description II

**Sketch(es)**




TYPE II TUNING PROCEDURE

**Sample Problem(s)** AFTER THE COMPONENT VALUES ARE CALCULATED, THE INDUCTORS FABRICATED AND TRIMMED TO THE DESIGN VALUE, AND THE CAPACITORS SELECTED AND PADDED TO THE DESIGN VALUE, THE FILTER MAY BE ASSEMBLED AND TUNED SO IT WILL EXHIBIT THE DESIRED RESPONSE.

TUNING IS ACCOMPLISHED BY ADJUSTING ONE OF THE PARALLEL RESONANT TANK COMPONENTS (USUALLY THE INDUCTOR AT LOW FREQUENCIES, AND THE CAPACITOR AT HIGHER FREQUENCIES SUCH AS THIS EXAMPLE). THE TANK RESONANCE MUST TAKE THE COUPLING ELEMENTS INTO ACCOUNT.

1) TEMPORARILY PLACE A SHORT CIRCUIT AT LOCATION B AND ADJUST $C_1$ TO RESONATE L @ $f_0$ = 1 MHZ

2) REMOVE THE SHORT AT B AND TEMPORARILY PLACE SHORTS AT LOCATIONS A AND C. ADJUST C2 TO RESONATE L AT $f_0$ = 1 MHZ.

3) CONTINUE SHORTING OUT ADJACENT TANK CIRCUITS AND ADJUSTING FOR RESONANCE WITH SUCCESSIVE SHORTS AT B & D, C & E, AND D.

THIS WILL COMPLETE THE TUNING OF THE FILTER.

**Reference(s)** SEE THE FERROXCUBE CATALOG ENTITLED "LINEAR FERRITE MATERIALS AND COMPONENTS" FOR DETAILS ON THE INDUCTOR DESIGN. FOR AIR CORE COILS SEE CHAPTER 10 OF THE "RADIOTRON DESIGNERS HANDBOOK"

# User Instructions

| Type 8 | Type 9 | Type 10 | Type 11 | All Types |
|---|---|---|---|---|
| $f_{center}$ | BW | R | | |

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | OUTPUT DATA/UNITS |
|---|---|---|---|---|
| 1 | LOAD BOTH SIDES OF PROGRAM CARD | | | |
| 2 | KEY IN CENTER FREQUENCY IN HZ | $f_0$ | A | |
| 3 | KEY IN BANDWIDTH IN HZ | BW | B | |
| 4 | KEY IN TERMINATION RESISTANCE IN OHMS | R | C | |
| 5 | SELECT TYPE OF FILTER DESIRED | | | |
| | TYPE 8 | | f A | $C_1, L_1$<br>$C_{12}$<br>$C_2, L_2$<br>$C_{23}$<br>⋮<br>$C_n, L_n$ |
| | TYPE 9 | | f B | $C_1, L$<br>$L_{12}$<br>$C_2, L$<br>$L_{23}$<br>⋮<br>$C_n, L$ |
| | TYPE 10 | | f C | $C, L_1$<br>$L_{12}$<br>$C, L_2$<br>$C_{23}$<br>⋮<br>$C, L_n$ |
| | TYPE 11 | | f D | $C_1, L$<br>$C_{12}$<br>$C_2, L$<br>$L_{23}$<br>⋮<br>$C_n, L$ |
| | ALL TYPES IN SUCCESSION | | f E | |

# 97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | key in fc, calculate and store $2\pi f_c \rightarrow R_0$ |
| 002 | Pi | 16-24 | |
| 003 | × | -35 | |
| 004 | 2 | 02 | |
| 005 | × | -35 | |
| 006 | STO0 | 35 00 | |
| 007 | RTN | 24 | |
| 008 | *LBLB | 21 12 | key in BW calculate and store $\Phi_c = \frac{2\pi f_c}{2\pi BW} \Rightarrow R_1$ |
| 009 | Pi | 16-24 | |
| 010 | × | -35 | |
| 011 | 2 | 02 | |
| 012 | × | -35 | |
| 013 | RCL0 | 36 00 | |
| 014 | ÷ | -24 | |
| 015 | 1/X | 52 | |
| 016 | STO1 | 35 01 | |
| 017 | RTN | 24 | |
| 018 | *LBLC | 21 13 | key in R Store in $R_2$ |
| 019 | STO2 | 35 02 | |
| 020 | RTN | 24 | |
| 021 | *LBLE | 21 16 15 | calculate all types routine |
| 022 | GSBa | 23 16 11 | |
| 023 | GSBb | 23 16 12 | |
| 024 | GSBc | 23 16 13 | |
| 025 | GSBd | 23 16 14 | |
| 026 | RTN | 24 | |
| 027 | *LBLa | 21 16 11 | Type 8 Routine |
| 028 | SPC | 16-11 | print heading |
| 029 | 8 | 08 | |
| 030 | PRTX | -14 | |
| 031 | SPC | 16-11 | |
| 032 | CF0 | 16 22 00 | not last tank |
| 033 | CF1 | 16 22 01 | print common elt first |
| 034 | CF2 | 16 22 02 | use type 8 & 9 routine |
| 035 | GSB8 | 23 08 | Setup registers 3,4,5,&7 |
| 036 | GTO0 | 22 00 | gto elt calc loop |
| 037 | *LBLb | 21 16 12 | Type 9 routine |
| 038 | SPC | 16-11 | print heading |
| 039 | 9 | 09 | |
| 040 | PRTX | -14 | |
| 041 | SPC | 16-11 | |
| 042 | CF0 | 16 22 00 | not last tank |
| 043 | SF1 | 16 21 01 | print common elt last |
| 044 | CF2 | 16 22 02 | use type 8&9 routine |
| 045 | GSB8 | 23 08 | Setup registers 3,4,5,7 |
| 046 | RCL2 | 36 02 | change type 8 constants to type 9 constants |
| 047 | X² | 53 | |
| 048 | STX3 | 35-35 03 | |
| 049 | STX4 | 35-35 04 | |
| 050 | ST÷5 | 35-24 05 | |
| 051 | GTO0 | 22 00 | gto element calc loop |
| 052 | *LBLc | 21 16 13 | Type 10 routine |
| 053 | SPC | 16-11 | print heading |
| 054 | 1 | 01 | |
| 055 | 0 | 00 | |
| 056 | PRTX | -14 | |
| 057 | SPC | 16-11 | |
| 058 | CF0 | 16 22 00 | not last tank |
| 059 | CF1 | 16 22 01 | print common element first |
| 060 | SF2 | 16 21 02 | use type 10&11 routine |
| 061 | GSB8 | 23 08 | setup regs 4,5,3,7 |
| 062 | GTO0 | 22 00 | gto element calc loop |
| 063 | *LBLd | 21 16 14 | Type 11 routine |
| 064 | SPC | 16-11 | print heading |
| 065 | 1 | 01 | |
| 066 | 1 | 01 | |
| 067 | PRTX | -14 | |
| 068 | SPC | 16-11 | |
| 069 | CF0 | 16 22 00 | not last tank circuit |
| 070 | SF1 | 16 21 01 | print common elt last |
| 071 | SF2 | 16 21 02 | use type 10 & 11 routine |
| 072 | GSB8 | 23 08 | setup regs 3,4,5,7 |
| 073 | RCL2 | 36 02 | Change type 10 coeff's to type 11 |
| 074 | X² | 53 | |
| 075 | STX3 | 35-35 03 | |
| 076 | STX4 | 35-35 04 | |
| 077 | ST÷5 | 35-24 05 | |
| 078 | *LBL0 | 21 00 | element calculation loop |
| 079 | GSB9 | 23 09 | |
| 080 | X≥Y? | 16-35 | |
| 081 | GTO5 | 22 05 | |
| 082 | GSB7 | 23 07 | |
| 083 | GTO0 | 22 00 | |
| 084 | *LBL5 | 21 05 | |
| 085 | SF0 | 16 21 00 | |
| 086 | GSB9 | 23 09 | |
| 087 | GSB7 | 23 07 | |
| 088 | RTN | 24 | |
| 089 | *LBL2 | 21 02 | Type 10 & 11 sign reversing routine |
| 090 | SF2 | 16 21 02 | |
| 091 | RCL0 | 36 14 | |
| 092 | CHS | -22 | |
| 093 | STO0 | 35 14 | |
| 094 | × | -35 | |
| 095 | RTN | 24 | |
| 096 | *LBL3 | 21 03 | Type 10 & 11 routine |
| 097 | SF2 | 16 21 02 | test for element type |
| 098 | RCL0 | 36 14 | |
| 099 | X>0? | 16-44 | |
| 100 | GTO5 | 22 05 | |
| 101 | RCL9 | 36 09 | Calculate & print coupling element |
| 102 | CHS | -22 | |
| 103 | RCL5 | 36 05 | |
| 104 | × | -35 | |
| 105 | PRTX | -14 | |
| 106 | SPC | 16-11 | |
| 107 | RCL9 | 36 09 | store $(a_k \cdot a_{k+1})^{-1/2}$ in $(a_{k-1} \cdot a_k)^{-1/2}$ position |
| 108 | STO8 | 35 08 | |
| 109 | RTN | 24 | |
| 110 | *LBL5 | 21 05 | calculate and print coupling coefficient |
| 111 | RCL4 | 36 04 | |
| 112 | RCL9 | 36 09 | |

## REGISTERS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 $2\pi f_c$ | 1 $Q_c$ | 2 $R$ | 3 common element | 4 used | 5 used | 6 $n$ | 7 $k$ | 8 $(a_{k-1} \cdot a_k)^{-1/2}$ | 9 $(a_k \cdot a_{k+1})^{-1/2}$ |
| S0 $a_k$ | S1 $a_{n-1}$ | S2 $a_{n-2}$ | S3 $a_{n-3}$ | S4 $a_{n-4}$ | S5 $a_{n-5}$ | S6 $a_{n-6}$ | S7 $a_{n-7}$ | S8 $a_{n-8}$ | S9 $a_{n-9}$ |

| | | | | | |
|---|---|---|---|---|---|
| A $a_{n-10}$ | B $a_{n-11}$ | C $a_{n-12}$ | D $(-1)^k$ | E $a_{k+1}$ | I index |

# 97 Program Listing II

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 113 | ÷ | -24 | |
| 114 | PRTX | -14 | |
| 115 | SPC | 16-11 | |
| 116 | RCL9 | 36 09 | |
| 117 | STO8 | 35 08 | |
| 118 | RTN | 24 | |
| 119 | *LBL7 | 21 07 | Common element subroutine |
| 120 | F1? | 16 23 01 | Test common element printing order |
| 121 | GTO5 | 22 05 | |
| 122 | RCL3 | 36 03 | |
| 123 | PRTX | -14 | |
| 124 | *LBL5 | 21 05 | |
| 125 | F0? | 16 23 00 | last tank ? |
| 126 | GTO5 | 22 05 | |
| 127 | RCLI | 36 45 | |
| 128 | RCLE | 36 15 | |
| 129 | X⇄Y | -41 | |
| 130 | STOE | 35 15 | |
| 131 | × | -35 | |
| 132 | √X | 54 | |
| 133 | 1/X | 52 | |
| 134 | F2? | 16 23 02 | |
| 135 | GSB2 | 23 02 | |
| 136 | STO9 | 35 09 | |
| 137 | *LBL5 | 21 05 | |
| 138 | F0? | 16 23 00 | last tank ? |
| 139 | 0 | 00 | |
| 140 | RCL1 | 36 01 | |
| 141 | + | -55 | |
| 142 | RCL8 | 36 08 | Calculate and print |
| 143 | + | -55 | resonant element |
| 144 | RCL5 | 36 05 | |
| 145 | × | -35 | |
| 146 | PRTX | -14 | |
| 147 | RCL3 | 36 03 | recall common element |
| 148 | F1? | 16 23 01 | print last ? |
| 149 | PRTX | -14 | |
| 150 | SPC | 16-11 | |
| 151 | F0? | 16 23 00 | last tank ? |
| 152 | RTN | 24 | exit loop |
| 153 | F2? | 16 23 02 | type 10 or 11 ? |
| 154 | GTO3 | 22 03 | use type 10 & 11 routine |
| 155 | RCL4 | 36 04 | |
| 156 | RCL9 | 36 09 | Calculate & print |
| 157 | ÷ | -24 | type 8 or 9 mutual |
| 158 | PRTX | -14 | coupling element |
| 159 | SPC | 16-11 | |
| 160 | RCL9 | 36 09 | Shift $(a_k \cdot a_{k+1})^{-1/2}$ |
| 161 | STO8 | 35 08 | data |
| 162 | RTN | 24 | |
| 163 | *LBL8 | 21 08 | Type 8 or 10 constants |
| 164 | 0 | 00 | initialize registers |
| 165 | STO7 | 35 07 | 7 and 8 |
| 166 | STO8 | 35 08 | |
| 167 | GSB9 | 23 09 | increment k by 1 |
| 168 | RCLI | 36 45 | recall $a_k$ |
| 169 | STOE | 35 15 | Store $a_k$ |
| 170 | RCL2 | 36 02 | recall R |
| 171 | × | -35 | |
| 172 | RCL0 | 36 00 | recall $\omega_0$ |
| 173 | × | -35 | |
| 174 | 1/X | 52 | |
| 175 | STO4 | 35 04 | store $(a_k \omega_0 R)^{-1}$ |
| 176 | RCL1 | 36 01 | recall $Q_L$ |
| 177 | ÷ | -24 | |
| 178 | STO3 | 35 03 | store $(a_k \omega_0 Q_L R)^{-1}$ |
| 179 | RCLE | 36 15 | recall $a_k$ |
| 180 | RCL2 | 36 02 | |
| 181 | × | -35 | |
| 182 | RCL0 | 36 00 | recall $\omega_0$ |
| 183 | ÷ | -24 | |
| 184 | STO5 | 35 05 | store $\frac{a_k R}{\omega_0}$ |
| 185 | 1 | 01 | |
| 186 | STOD | 35 14 | setup register D |
| 187 | RTN | 24 | |
| 188 | *LBL9 | 21 09 | k incrementing routine |
| 189 | 1 | 01 | |
| 190 | ST+7 | 35-55 07 | |
| 191 | RCL7 | 36 07 | |
| 192 | 9 | 09 | |
| 193 | + | -55 | |
| 194 | STOI | 35 46 | |
| 195 | RCL7 | 36 07 | recall variables |
| 196 | RCL6 | 36 06 | for exit test |
| 197 | 1 | 01 | |
| 198 | + | -55 | |
| 199 | RTN | 24 | |

## LABELS

| | | | | |
|---|---|---|---|---|
| A Store $2\pi f_c \to R_0$ | B Store $Q_L = f_0/BW \to R_1$ | C Store $R \to R_2$ | D not used | E not used |
| a Type 8 Start | b Type 9 Start | c Type 10 Start | d Type 11 Start | e all types start |
| 0 element calc loop start | 1 not used | 2 Type 10 & 11 Sign Reverse | 3 Type 10 or 11 mutual elt routine | 4 not used |
| 5 Local dot. label | 6 not used | 7 Element value subr. start | 8 fixed constant calculation | 9 increment k & test for loop exit |

## FLAGS

| | |
|---|---|
| 0 | Last tank ckt. |
| 1 | print common elt last |
| 2 | indicates type 10 or 11 filter |
| 3 | not used |

## SET STATUS

| FLAGS | ON | OFF |
|---|---|---|
| 0 | ☐ | ■ |
| 1 | ☐ | ■ |
| 2 | ☐ | ■ |
| 3 | ☐ | ■ |

| TRIG | |
|---|---|
| DEG | ☐ |
| GRAD | ■ |
| RAD | ☐ |

| DISP | |
|---|---|
| FIX | ☐ |
| SCI | ■ |
| ENG | ☐ |
| n | 3 |

# Program Description I

| | |
|---|---|
| Program Title | NORMALIZED LOWPASS TO BANDSTOP, LOWPASS, OR HIGHPASS TRANSFORMATION |
| Contributor's Name | Bruce K. Murdock |
| Address | 6875 Sabado Tarde Rd. |
| City | Goleta State Calif Zip Code 93017 |

**Program Description, Equations, Variables**

This program converts the normalized lowpass coefficients (1 Ohm, 1 rad/sec), generated by another program of this set, into the frequency and impedance scaled lowpass, highpass, and bandstop topologies. Two forms of each transformation are given. These forms are the duals of one-another. All these transformations are exact (classical) and are applicable for any impedance level, bandwidth, and in the bandstop case, center frequency. One should consult White's table 7.1 to determine the physical realizability of a particular filter requirement. This table is reproduced herein.

The program is separated into three parts which share common subroutines. These sections are 1) de-normalization parameter input (bandwidth, termination resistance level, and center frequency), 2) bandstop denormalization and transformation, and 3) lowpass and highpass denormalization and transformation.

These program sections will be described in separate sections of this description.

**Operating Limits and Warnings** This program obtains the normalized lowpass coefficients from register storage in the secondary set of registers. The filter order, n, is also stored. One should first run the lowpass normalized coefficient program, or manually place the desired lowpass normalized coefficients and filter order in register storage before running this program.

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

HIGHPASS, BANDPASS, AND BANDSTOP TRANSFORMATIONS IN ANALYTICAL FORM

1) HIGHPASS TRANSFORMATION

The highpass transformation is accomplished by replacing s, the complex operator, by 1/s. Since sinusoidal frequencies are of prime interest, s may be replaced by jw, or 1/s by -j/w. For example, the magnitude response of the Butterworth normalized lowpass is:

$$|A(\omega)|_{LP} = \frac{1}{\sqrt{1+\omega^{2n}}}$$

The highpass transformed magnitude response is:

$$|A(\omega)|_{HP} = \sqrt{\frac{\omega^{2n}}{1+\omega^{2n}}}$$

For a detailed explanation see Louis Weinberg, "Network Analysis and Synthesis", McGraw-Hill, copyright 1962, chapter 11. Also see Zverev.

2) BANDPASS TRANSFORMATION

The bandpass transformation is accomplished by replacing s by s+1/s (normalized). This equation may be denormalized to the design center frequency, $w_o$, and the design bandwidth, $w_c$. The transformation equation becomes:

$$s \Rightarrow Q_L\left\{\frac{s}{\omega_o} + \frac{\omega_o}{s}\right\} \quad \text{where} \quad Q_L = \frac{\omega_o}{\omega_c} = \frac{\text{center frequency}}{\text{bandwidth}}$$

When the transformation is applied to the Butterworth lowpass magnitude equation, and s is replaced by jw, the following results:

$$|A(\omega)|_{B.P} = \left\{1 + \left(Q_L\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right)\right)^{2n}\right\}^{-1/2}$$

Again, for a detailed explanation, see Weinberg or Zverev.

3) BANDSTOP TRANSFORMATION

The bandstop transformation is to the bandpass transformation, as the highpass transformation is to the lowpass, i.e. they are reciprocals, hence, the normalized bandstop transformation is to replace s by 1/(s+1/s). As with the bandpass, this equation may be denormalized to the operating impedance and bandwidth. The denormalized equation with s replaced by jw becomes:

$$\omega \Rightarrow 1\Big/\left(Q_L\left\{\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right\}\right)$$

The Butterworth equation for the lowpass magnitude response transforms thus:

$$|A(\omega)|_{B.S.} = \left\{\frac{\left[Q_L\left\{\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right\}\right]^2}{1 + \left[Q_L\left\{\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right\}\right]^2}\right\}^{1/2}$$

The subject of bandstop filters is generally avoided, or discussed lightly by most authors. No particularly good reference exists unfortunately. All of the narrowband approximations and transformations that have been derived for the bandpass case should be derivable for the bandstop filter in an analogous manner.

The best reference, in terms of detail, is Matthaei, Young, and Jones, "Microwave filters, impedance matching networks, and coupling structures" McGraw-Hill, copyright 1964, chapter 12.

# Program Description I

The physical realizability of a filter topology is assigned one of four possible scores based upon the element values. These scores are defined as follows:

Readily Realizable (R)

$1\ uHy \le L \le 1\ Hy$
$5\ pF \le C \le 1\ uF$

Practical (P)

$0.2\ uHy \le L \le 10\ Hy$
$2.\ pF \le C \le 10\ uF$

Marginally practical (M)

$50\ nHy \le L \le 100\ Hy$
$0.5\ pF \le C \le 500\ uF$

Impractical (I)

All element values that lie outside the range of Marginal i. e.,

$L < 50\ nHy$
$L > 100\ Hy$
$C < .5\ pF$
$C > 500\ uF$

The table headings are meant to indicate ranges of loaded Q, filter center frequency, and impedance level. These ranges are defined as follows:

Frequency,

$f_o = 10$ Hz implies: $3\ Hz \le f_o < 30\ Hz$
$f_o = 100$ Hz implies: $30\ Hz \le f_o < 300\ Hz$
$f_o = 1$ kHz implies: $300\ Hz \le f_o < 3\ kHz$
$f_o = 10$ kHz implies: $3\ kHz \le f_o < 30\ kHz$
$f_o = 100$ kHz implies: $30\ kHz \le f_o < 300\ kHz$
$f_o = 1$ mHz implies: $300\ kHz \le f_o < 3\ mHz$
$f_o = 10$ mHz implies: $3\ mHz \le f_o < 30\ mHz$
$f_o = 100$ mHz implies: $30\ mHz \le f_o < 300\ mHz$

At frequencies above 300 mHz, lumped element filters are generally replaced with transmission line type filters.

Loaded Q ($Q_L$), for bandpass and bandstop,

$Q_L = 5$ implies: $3 \le Q_L < 10$
$Q_L = 15$ implies: $10 \le Q_L < 30$
$Q_L = 50$ implies: $30 \le Q_L \le 100$

Impedance Level (source and load resistances equal)

$R = 3$ Ohms implies: $1 \le R < 10$ (power filters)
$R = 50$ Ohms implies: $10 \le R < 150$
$R = 500$ Ohms implies: $150 \le R < 2.5k$
$R = 10$ kOhms implies: $2.5k \le R < 50k$

# Program Description I

Table 7.1
PHYSICAL REALIZABILITY OF LOW- AND HIGH-PASS FILTERS

| R in ohms | Cut Off Frequency, $f_c$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 10 cps | 100 cps | 1 kc | 10 kc | 100 kc | 1 mc | 10 mc | 100 mc |
| 3 | I | M | M | P | R | P | M | I |
| 50 | M | M | M | R | R | R | R | M |
| 500 | M | P | R | R | R | R | R | R |
| 10k | I | M | P | R | R | R | P | I |

Courtesy, Don White Consultants Inc.

# Program Description I

## LOWPASS FILTERS

No transformation is involved here, one need only frequency and impedance scale the normalized lowpass values to the desired bandwidth and termination resistance level. The object of the scaling procedure is to end up with filter elements that have the same impedance ratios to the termination resistance at the operating cutoff frequency and resistance as the normalized lowpass did at 1 radian/second and 1 ohm. The mechanics of the scaling procedure are:

$$L, \text{ scaled} = (L, \text{ normalized})\cdot(R/(2\pi BW))$$

$$C, \text{ scaled} = (C, \text{ normalized})\cdot(1/(2\pi(BW)R))$$

Where BW, and R represent the design bandwidth and termination resistance respectively.

EXAMPLE:

A maximally flat (Butterworth) lowpass filter is needed to pass a 1 kHz signal with 1 dB or less attenuation (from the value at zero frequency) and reject a 12 kHz signal by at least 75 dB. The filter order solution is outside the range of the nomographs as $\lambda = 12$ kHz/1 kHz = 12 and the $\lambda$ scale ends at 10. The nomographs are in the lowpass normalized Butterworth and Chebychev coefficient program. One may solve for n by using another program of this set, or by using the equation at the bottom of the nomograph for Butterworth filters i.e. $As^2-1 = (Ap^2-1)\lambda^{2n}$. This equation may be rearranged to solve for n:

$$n = \frac{\log\left\{\frac{A_s^2-1}{A_p^2-1}\right\}}{2\log\lambda}$$

Where As and Ap are the ratio equivalents of those quantities expressed in dB, i.e.

$$A_s^2 = 10^{(As(dB))/10} \quad ; \quad A_p^2 = 10^{(Ap(dB))/10}$$

Substitution of these values yields n=3.7. Since n must be integral, use n=4.

Load the normalized lowpass coefficient program to obtain and store the Butterworth coefficients for n=4. The present program may then be loaded for scaling these coefficients to the desired cutoff frequency, and resistance level (1000 Ohms). The normalized Butterworth coefficients define a filter that is 3 dB down at the cutoff frequency, and the 3 dB frequency may be found from the Butterworth equation knowing n and the 1 dB frequency. i.e.

$$\lambda = \left\{\frac{A_s^2-1}{A_p^2-1}\right\}^{1/2n} \quad \text{where} \quad As^2 = 10^{(As(dB))/10}, \quad Ap^2 = 10^{(Ap(dB))/10}, \quad n = 4$$

$\lambda = 1.183301$ , then

$$f_{-3dB} = (\lambda)\cdot(f_{-1dB}) = (1.183301)\cdot(1000 \text{ Hz}) = 1183.301 \text{ Hz.}$$

# Program Description

The printer output is shown at the left, below. The two forms of the denormalized lowpass are shown at the bottom of the page.

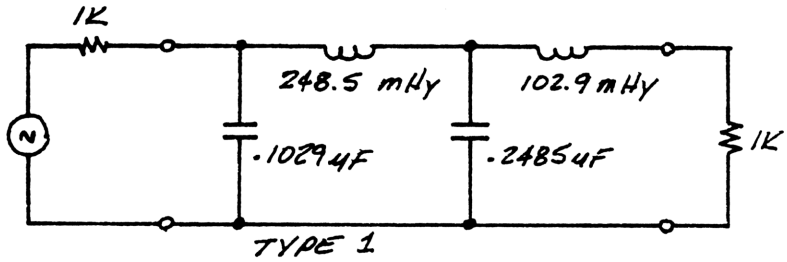
Lowpass normalized program

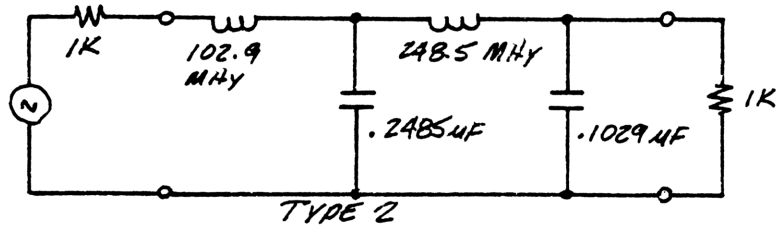
```
      n =  4.000000 GSBA
 Butterworth  →   GSBa

      a1    0.765367  ***
      a2    1.847759  ***
      a3    1.847759  ***
      a4    0.765367  ***
```

load this program

```
Bandwidth   1163.301 GSBB
Resistance     1000. GSBC
Lowpass form 1  →  GSBa

                31.

      C1    102.9-09  ***
      L2    248.5-03  ***
      C3    248.5-09  ***
      L4    102.9-03  ***
```

```
Lowpass form 2  →  GSBb

                32.

      L1    102.9-03  ***
      C2    248.5-09  ***
      L3    248.5-03  ***
      C4    102.9-09  ***
```

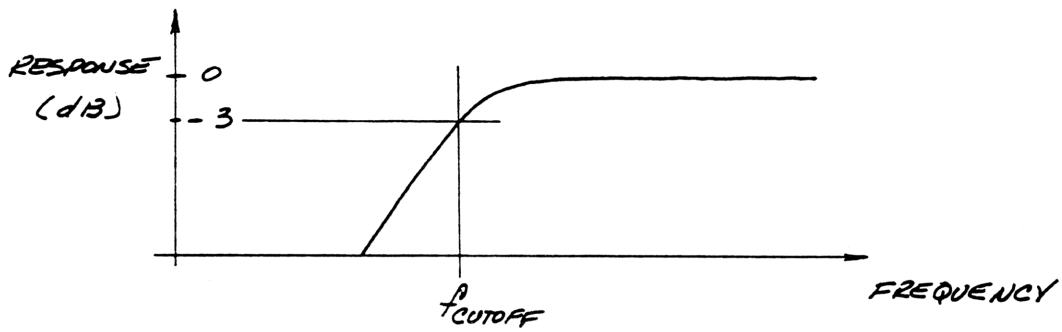


# Program Description

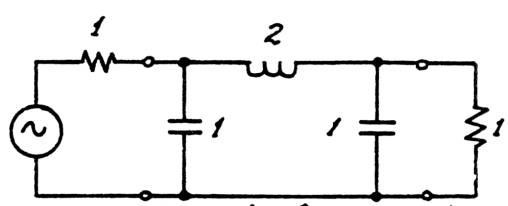
## HIGHPASS FILTERS

The highpass filter is the opposite of the lowpass filter, i.e. it passes frequencies above the cutoff frequency, and blocks those below the cutoff frequency. The figure below graphically shows this characteristic.

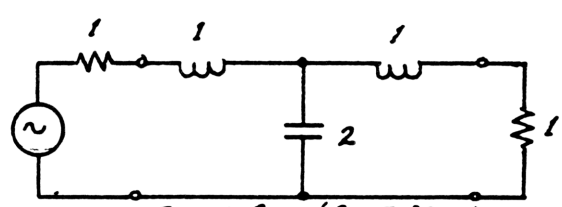



Conceptually the transformation is accomplished by replacing each capacitor with an inductor, and vice versa in the lowpass structure. The normalized highpass component values are the recipricals of the normalized lowpass values.

EXAMPLE: The two forms of a third order normalized Butterworth filter are:

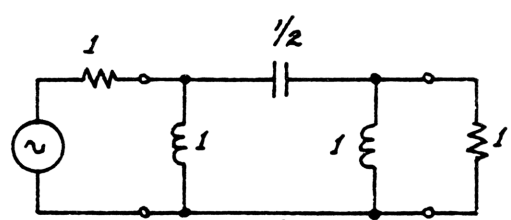



FORM 1 (CODE "31")

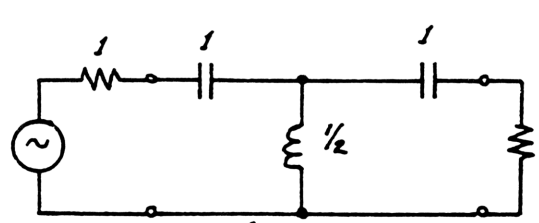



FORM 2 (CODE "32")

The normalized highpass transforms are:




FORM 1 (CODE "41")




FORM 2 (CODE "42")

# Program Description I

Once the normalized highpass transformation has been made, the normalized filter may be scaled to the desired cutoff frequency, and impedance level in the same manner as was used in the lowpass case.

$$L_{scaled} = L_{normalized} \left\{ R/(2\pi(BW)) \right\}$$

$$C_{scaled} = C_{normalized} \left\{ 1/(2\pi(BW) \cdot R) \right\}$$

Where BW and R represent the operating cutoff frequency and resistance level respectively.

EXAMPLE: A highpass filter is needed in the antenna lead of a tv set to reject the carrier signal from a nearby amateur radio transmitter as this signal is strong enough to cause cross modulation in the tuner of the tv set. The low end of channel 2's spectrum is 54 mHz, and the transmitter is operating at 28 mHz. 1 dB of attenuation and ripple will be allowed across the tv spectrum. At least 60 dB of attenuation is required at 28 mHz. The filter is to be placed in a 300 Ohm balanced line. Because of the allowed ripple, a Chebychev filter may be used. One may use the Chebychev nomograph, or another program of this set to solve for the filter order, n. Using the nomograph and entering Ap=1 dB, As=60dB, and $\lambda$=54 mHz/28mHz = 1.93 yields n=6.4; n must be integral, use n=7.

When designing balanced filters, i.e. filters to go into balanced lines, the unbalanced filter structure may be transformed into a balanced structure by either of two methods. Both methods yield the same result. One way is to design the filter at an impedance level that is ½ the desired level, then draw the unbalanced filter plus it's mirror image below the common line. The common line is erased, and shunt elements combined. The other way is to design the filter at the desired impedance level, and then to replace each series element with two series elements having the same total impedance. One of these new series elements is then placed in the common line opposite the mate. This method will be used in this example.

The HP-97 printer output is shown at the left on the next page, and the two unbalanced, and two balanced forms of the highpass filter shown.

First the normalized Chebychev lowpass coefficient program is loaded to obtain the 7th order, 1 dB Chebychev lowpass normalized coefficients, and to have them automatically stored in the secondary registers for use by this program. Next this program is loaded, and the denormalized highpass element values calculated.

# Program Description

LOAD NORMALIZED LOWPASS PROGRAM

KEY IN $n$ = 7.000000 GSBA
KEY IN $G_{dB}$ = 1.000000 GSBB
$\omega_{-3dB}$ = 1.017205 ***

$G_1$ = 2.166557 ***
$G_2$ = 1.111509 ***
$G_3$ = 3.093642 ***
$G_4$ = 1.173521 ***
$G_5$ = 3.093642 ***
$G_6$ = 1.111509 ***
$G_7$ = 2.166557 ***

LOAD THIS PROGRAM

BANDWIDTH = 54.+06 GSBB
$R$ = 300. GSBC
CALCULATE HIGHPASS "1" → GSBc

HIGHPASS "1" CODE 41.

$L_1$ = 408.1-09 ***
$C_2$ = 8.839-12 ***
$L_3$ = 285.8-09 ***
$C_4$ = 8.372-12 ***
$L_5$ = 285.8-09 ***
$C_6$ = 8.839-12 ***
$L_7$ = 408.1-09 ***

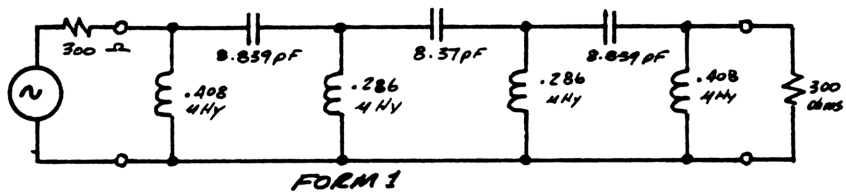
HIGHPASS "2" GSBd

CODE 42.

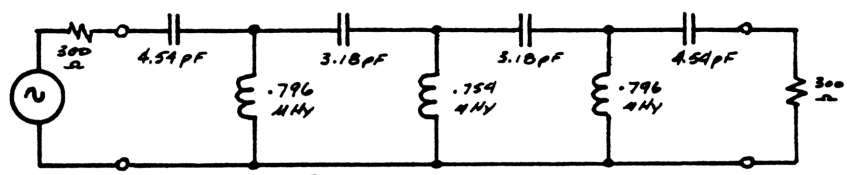
$C_1$ = 4.535-12 ***
$L_2$ = 795.5-09 ***
$C_3$ = 3.176-12 ***
$L_4$ = 753.5-09 ***
$C_5$ = 3.176-12 ***
$L_6$ = 795.5-09 ***
$C_7$ = 4.535-12 ***

SCHEMATICALLY, THE FILTERS ARE

1) UNBALANCED 300 OHM FILTERS:

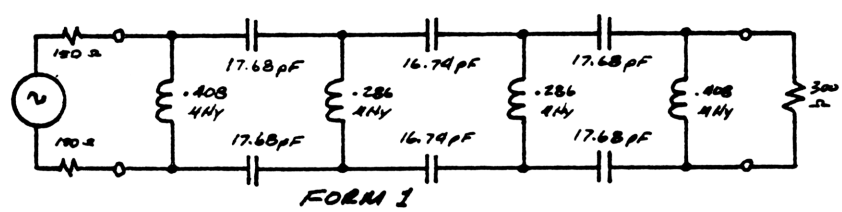



FORM 1

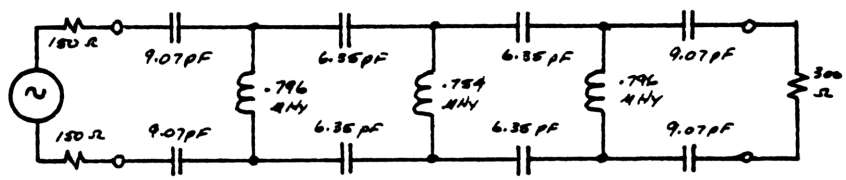



FORM 2

2) EQUIVALENT BALANCED FILTER FORMS




FORM 1



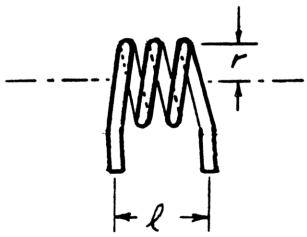

FORM 2

# Program Description

## INDUCTOR DESIGN

Most of the other examples in this filter program set have been at lower operating frequencies, and the inductors can be easily fabricated using ferrite pot cores. At the frequencies involved in this example, air core and slug tuned inductors are a more practical choice.

With these inductors, a method for estimating the winding parameters to generate the required inductance is required. Wheeler's formula may be employed for this estimate.




$$L(uHy) = \frac{r^2 n^2}{9r + 10^{-1}}$$

where n is the number of turns
r is the radius in inches
l is the length in inches

Wheelers formula is accurate to 1% for all values of $2r/l < 3$ . The calculated inductance will be about 4% low when $2r/l = 5$ .

The coil "Q", or quality factor, may also be estimated using Callender's equation:

$$Q = \frac{\sqrt{f(Hz)}}{\frac{2.71}{r} + \frac{2.13}{l}}$$

This equation is accurate to within a few percent provided the spacing between coil turns is at least twice the wire diameter. For close wound coils, the calculated Q will be high by a factor of 1.9 .

These formulae may be applied to the design of the inductors needed for the highpass filter. Form 2 of the highpass design will be used.

The inductance formula (Wheeler's formula) can be rewritten so that the inductance is one of the independant variables, and the number of turns is the dependant variable. The quantities n, and l may be related if a coil winding pitch is defined. Let $p = n/l$ , then $l = n/p$ , and Wheeler's equation may be rewritten thus:

$$n^2 r^2 - 10\frac{L}{p} n - 9rL = 0$$

This equation is quadratic in form, and n may be obtained through use of the quadratic formula to yield:

$$n = \frac{5L(\mu Hy)}{r^2 p} \cdot \left\{ 1 + \sqrt{1 + \frac{.36 r^3 p^2}{L}} \right\}$$

# Program Description I

Two values of inductance are needed for the series elements in form 2 of the highpass filter. These values are .796, and .754 microhenry. If #20 AWG wire is used (.0320 inch diameter), and a winding pitch is chosen so that the turn spacing is twice the wire diameter, and a $\frac{1}{2}$ inch form is used, a standard B&W airdux may be used. With these winding parameters, the following turns requirements result:

| | | |
|---|---|---|
| .796 uHy | 10.8 turns | (.7" long) |
| .754 uHy | 10.3 turns | (.66" long) |

Callender's equation predicts a Q of about 525 for these coils.

Another way of fabricating these inductors would be to use a slug tuned coil form such as a J.W. Miller p/n 25A014-4 (.2" dia X .6" long) with a carbonyl J tuning slug. 12 turns of #18 AWG HF wire on this form make an inductor that can be tuned to either one of the above values, and exhibits a Q of about 150.

For the highpass example either of the above inductor designs would work. The design using the slug tuning would be easier to adjust. In the highpass case, either design has adequately high Q.

In the bandpass, or bandstop cases, the requirements on resonator Q are much more stringent. One has two choices here, either make the resonator Q's much greater than the loaded Q of the filter (center freq/bandwidth), or predistort the filter design to use resonators with all Q's equal. A good reference for the predistorting technique is: Blinchikoff and Zverev, "Filtering in the Time and Frequency Domains", Wiley-Interscience, c 1976, chapter 6. A reference on how much greater the resonator Q must be than the filter Q is: Donald R. J. White," A Handbook on Electrical Filters", White Electromagnetics Inc, c 1963, chapter 6.

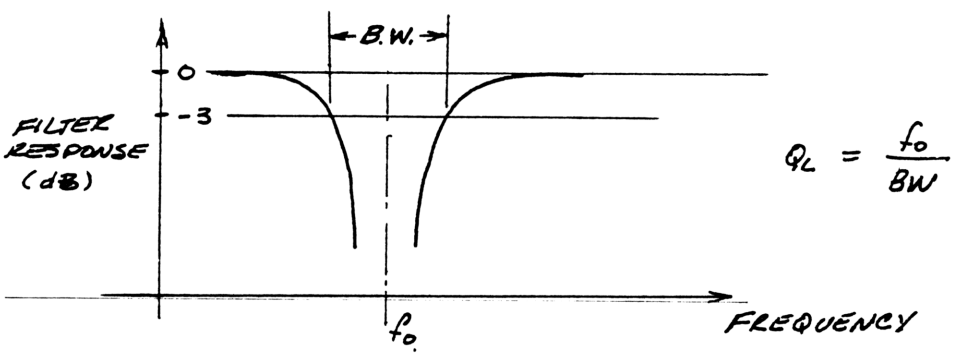
# Program Description I

## BANDSTOP TRANSFORMATION

The bandstop filter transmits all frequencies except those lying within a given band of frequencies called the stopband. A subclass of this family of filters are sometimes called notch filters. A typical use of such a filter would be to remove interference, or unwanted signals from within a wanted spectrum. An example would be to place a notch filter in the antenna lead of a t v set to remove the spectrum of a strong station and prevent it from causing cross modulation in the tuner when tuned to an adjacent weak tv station.

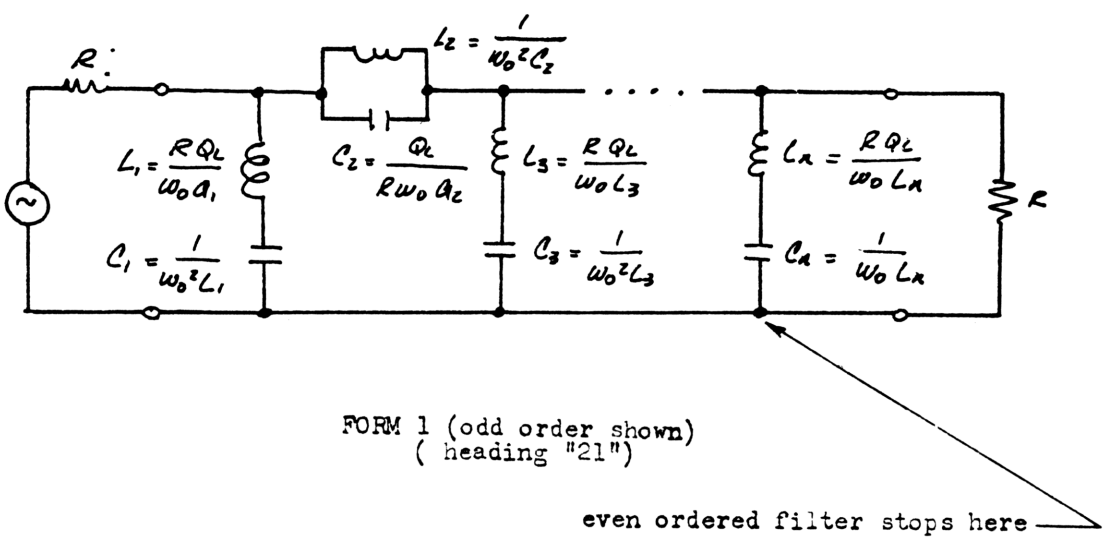
Conceptually the transformation is accomplished by designing a highpass filter whose cutoff frequency equals the bandwidth of the desired bandstop filter. Each shunt inductor in the highpass filter is series resonated with a capacitor at the desired center frequency of the filter. Likewise, each series capacitor is parallel resonated with an inductor at the desired center frequency.

The filter parameters may be defined with the aid of a figure:




$$Q_L = \frac{f_0}{BW}$$

If $a_1, a_2, \ldots, a_n$ are the normalized lowpass coefficients, one form of the bandstop filter is:

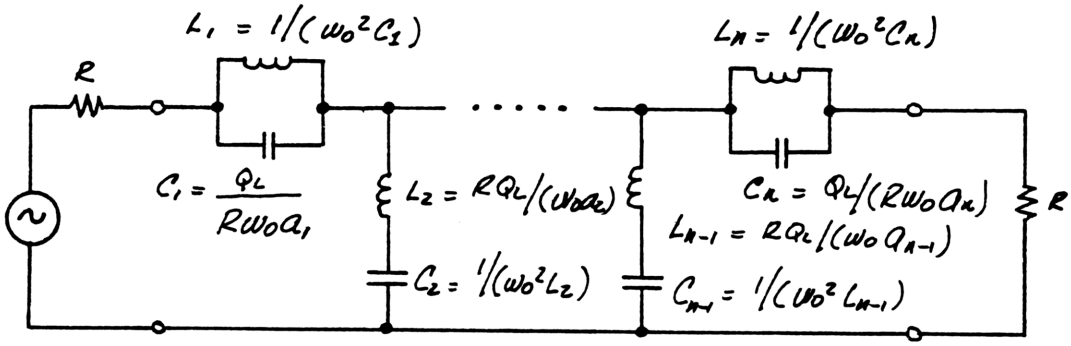



FORM 1 (odd order shown)
( heading "21")

even ordered filter stops here

# Program Description I

The other form of this filter is the dual of the first:




FORM 2 (heading "22")

The program solves for either form 1 (heading "21"), or form 2 (heading "22") of the bandstop filter given the normalized lowpass coefficients (from the program of the same name in this set), the center frequency, the bandwidth, and the termination resistance level.

The operation of the program can be illustrated by means of an example. A bandstop filter is needed to remove the spectrum of tv channel 3 prior to the tuner to cure a cross-modulation problem on distant channels 2 and 4. The filter will be in a 75 Ohm coax system. It has been experimentally determined that 20 dB of attenuation in the central 4.5 mHz of the 6 mHz wide tv channel will solve the problem. The filter will be designed to have a 1 dB bandwidth of 6 mHz. The center of channel 3 is 63 mHz. A Chebychev approximation will be used with 1 dB of ripple outside the stopband.

One may use the Chebychev nomograph to determine the required filter order. Entering the nomograph at Ap = 1 dB, As = 20 dB, and $\lambda = 6/4.5 = 1.333....$ the required filter order is 4.5 . since n must be integral, use n = 5.

First the normalized lowpass coefficient program is loaded to obtain and store the fifth order, 1 dB Chebychev coefficients, then this program is loaded to perform the bandstop transformation for a center frequency of 63 mHz, a bandwidth of 6 mHz, and a termination resistance level of 75 Ohms.

The HP-97 printout is shown on the next page for the above operations, and the two forms of the bandstop filter are shown schematically.

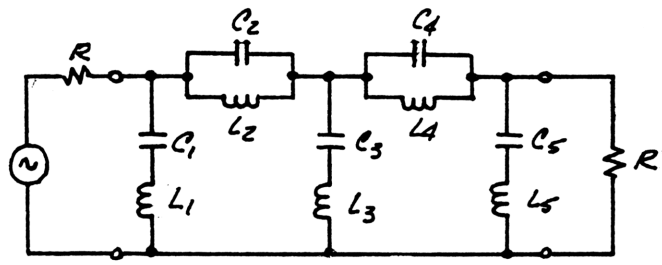
# Program Description

LOWPASS NORM COEF PROGRAM

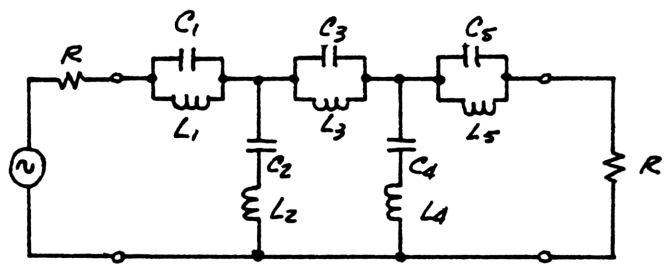
```
input { n =   5.000000 GSBA
      { GdB   1.000000 GSBB
ω-3dB =       1.033815  ***

G1    2.134882  ***
G2    1.091107  ***
G3    3.000923  ***
G4    1.091107  ***
G5    2.134882  ***
```

LOAD BANDSTOP TRANSFORMATION PROGRAM (THIS PROGRAM)

```
Center freq      63.+06 GSBA
Bandwidth         6.+06 GSBB
Termination Resis.  75. GSBC
Bandstop form 1       GSBD

Bandstop1 code "21."

C1 =   6.849-12  ***
L1 =   931.9-09  ***

C2 =   324.1-12  ***
L2 =   19.69-09  ***

C3 =   9.627-12  ***
L3 =   662.9-09  ***

C4 =   324.1-12  ***
L4 =   19.69-09  ***

C5 =   6.849-12  ***
L5 =   931.9-09  ***

Bandstop form 2       GSBE

Bandstop2 code "22."

C1 =   165.7-12  ***
L1 =   38.52-09  ***

C2 =   3.500-12  ***
L2 =   1.823-06  ***

C3 =   117.9-12  ***
L3 =   54.15-09  ***

C4 =   3.500-12  ***
L4 =   1.823-06  ***

C5 =   165.7-12  ***
L5 =   38.52-09  ***
```




FORM 1




FORM 2

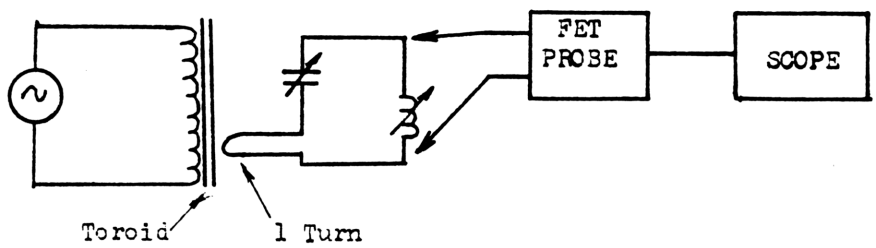
In this particular example, form 2 is more physically realizable than is form 1. In form 1, L2 = 19.7 nHy which parallel resonates with C2 = 324 pF. The measured self inductance of a 330 pF silvered mica capacitor is 7.0 nHy ( 105 mHz self resonant frequency) About half of the required resonating inductance is already within the capacitor, which would hinder the coupling into such a tank circuit. The remaining 12.7 nHy is the inductance of a .6 inch piece of straight #16 wire!

By contrast, L1 in form 2 is 38.5 nHy, and is resonated by a 165.7 pF capacitor. The measured self inductance of a 160 pF silvered mica capacitor with it's leads bent tightly against the case is 5.5 nHy (170 mHz resonant frequency). This value of lead inductance can be absorbed in the resonating inductor. The resonant tank consists of the 160 pF capacitor, and 3/4 turn of #18 AWG on a 0.2 inch dia. form with a Carbonyl J tuning slug.

# Program Description

## TUNING THE FILTER

The bandstop filter, like the bandpass filter, requires tuning after construction. In form 1, and form 2 of the bandstop, as well as form 1, and form 2 of the bandpass, the tuning procedure is to tune each individual tank to resonance at the center frequency of the filter. To accomplish this resonance adjustment, each parallel tank, and each series tank must be decoupled from their neighbors. At lower frequencies (certantly below 500 kHz) many methods exist for coupling into the tank. For example, a small resistance may be introduced into the bottom of the inductor, and a small voltage impressed across this resistance. Another way is to pass one lead of the inductor through the eye of a toroid which already has a winding on it, thus forming a one turn secondary. With the FET probes available for scopes, one may monitor the voltage across the tank with negligable loading. To tune a tank in such an arrangement, the one turn transformer is driven with a sinusoidal source at the desired resonant frequency, and the inductor,or capacitor adjusted to obtain a peaking of the voltage across the tank inductor. The figure below depicts such a tuning setup.




At higher frequencies, such as the bandstop example, coupling becomes more difficult. It is also difficult to keep the additional parasitic capacitance and inductance thus introduced from contaminating the tuning adjustment. For example, one might couple into the tanks with a dip meter search coil, measure the dip oscillator frequency with a counter, and adjust the tank elements until resonance is detected. When the resonant capacitor in the tank circuit is 6.8 pF, the few tenths of a picofarad that the search coil introduces by being in the proximity will have a measureable effect on the tuning. Another way that is probably more accurate, but is less direct, is to drive the filter with s sweep oscillator and detector, and adjust the filter for the desired response. This method has other merits also, as the filter load may be connected during tuning, and any stray capacity or inductance compensated for.

# User Instructions

| | | | | | |
|---|---|---|---|---|---|
| Lowpass Type 1 | Lowpass Type 2 | Highpass Type 1 | Highpass Type 2 | | 2 |
| $f_{center}$ | BW | R | Bandstop Type 1 | Bandstop Type 2 | |

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1 | LOAD PROGRAM | | | | |
| 2 | FOR LOWPASS COMPONENT VALUES | | | | |
| | a) LOAD BANDWIDTH (CUTOFF FREQ) | BW | | B | 2π BW |
| | b) LOAD RESISTANCE LEVEL | R | | C | R |
| | c) FOR TYPE 1 FILTER | | f | A | $C_1$ |
| | | | | | $L_2$ |
| | | | | | $C_3$ |
| | | | | | ⋮ |
| | | | | | $C_n$ or $L_n$ |
| | d) FOR TYPE 2 FILTER | | f | B | $L_1$ |
| | | | | | $C_2$ |
| | | | | | $L_3$ |
| | | | | | ⋮ |
| | | | | | $L_n$ or $C_n$ |
| 3 | FOR HIGHPASS COMPONENT VALUES | | | | |
| | a) LOAD CUTOFF FREQUENCY | $f_{cutoff}$ | | B | 2π fc |
| | b) LOAD RESISTANCE LEVEL | R | | C | R |
| | c) FOR TYPE 1 FILTER | | f | C | $L_1$ |
| | | | | | $C_2$ |
| | | | | | $L_3$ |
| | | | | | ⋮ |
| | | | | | $C_n$ or $L_n$ |
| | d) FOR TYPE 2 FILTER | | f | D | $C_1$ |
| | | | | | $L_2$ |
| | | | | | $C_3$ |
| | | | | | ⋮ |
| | | | | | $L_n$ or $C_n$ |

# User Instructions

1 CONTINUED FROM PREVIOUS PAGE 2

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 4 | FOR BANDSTOP COMPONENT VALUES | | | | |
| | a) LOAD CENTER FREQ | $f_{center}$ | | A | $2\pi f_c$ |
| | b) LOAD BANDWIDTH | BW | | B | $2\pi BW$ |
| | c) LOAD RESISTANCE LEVEL | R | | C | R |
| | d) FOR TYPE 1 FILTER | | | D | $C_1$ |
| | | | | | $L_1$ |
| | | | | | $C_2$ |
| | | | | | $L_2$ |
| | | | | | ⋮ |
| | | | | | $C_n$ |
| | | | | | $L_n$ |
| | e) FOR TYPE 2 FILTER | | | | $C_1$ |
| | | | | | $L_1$ |
| | | | | | $C_2$ |
| | | | | | $L_2$ |
| | | | | | ⋮ |
| | | | | | $C_n$ |
| | | | | | $L_n$ |

# 97 Program Listing I

09408 D

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | enter center freq. |
| 002 | Fi | 16-24 | multiply by 2π |
| 003 | 2 | 02 | |
| 004 | × | -35 | |
| 005 | × | -35 | |
| 006 | STO0 | 35 00 | store $2\pi f_c$ |
| 007 | RTN | 24 | |
| 008 | *LBLB | 21 12 | enter bandwidth |
| 009 | Fi | 16-24 | multiply by 2π |
| 010 | × | -35 | |
| 011 | 2 | 02 | |
| 012 | × | -35 | |
| 013 | STO1 | 35 01 | store 2πBW |
| 014 | RTN | 24 | |
| 015 | *LBLC | 21 13 | enter resistance |
| 016 | STO2 | 35 02 | store resistance |
| 017 | RTN | 24 | |
| 018 | *LBLD | 21 14 | Bandstop Type 1 |
| 019 | SPC | 16-11 | print heading |
| 020 | 2 | 02 | "21" |
| 021 | 1 | 01 | |
| 022 | PRTX | -14 | |
| 023 | SPC | 16-11 | |
| 024 | CF1 | 16 22 01 | establish print |
| 025 | GTO0 | 22 00 | order. |
| 026 | *LBLE | 21 15 | Bandstop type 2 |
| 027 | SPC | 16-11 | print heading |
| 028 | 2 | 02 | "22" |
| 029 | 2 | 02 | |
| 030 | PRTX | -14 | |
| 031 | SPC | 16-11 | |
| 032 | SF1 | 16 21 01 | estab print order |
| 033 | *LBL0 | 21 00 | calc bandstop coefs |
| 034 | RCL2 | 36 02 | R |
| 035 | RCL1 | 36 01 | 2πBW |
| 036 | × | -35 | |
| 037 | RCL0 | 36 00 | $w_o$ |
| 038 | $X^2$ | 53 | |
| 039 | ÷ | -24 | |
| 040 | STO4 | 35 04 | |
| 041 | RCL2 | 36 02 | |
| 042 | $X^2$ | 53 | |
| 043 | ÷ | -24 | |
| 044 | STO5 | 35 05 | |
| 045 | 0 | 00 | initialize k |
| 046 | STO7 | 35 07 | |
| 050 | | | |

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 047 | *LBL1 | 21 01 | Bandstop loop |
| 048 | GSB9 | 23 09 | increment k |
| 049 | X≤Y? | 16-35 | test for loop exit |
| 050 | RTN | 24 | |
| 051 | RCLi | 36 45 | $a_k$ |
| 052 | RCL4 | 36 04 | |
| 053 | CF0 | 16 22 00 | |
| 054 | F1? | 16 23 01 | test for printorder |
| 055 | GTO6 | 22 06 | |
| 056 | CLX | -51 | |
| 057 | RCL5 | 36 05 | |
| 058 | SF0 | 16 21 00 | |
| 059 | *LBL6 | 21 06 | |
| 060 | GSB8 | 23 08 | calc & print elts. |
| 061 | GSB9 | 23 09 | increment k |
| 062 | X≤Y? | 16-35 | test for loop exit |
| 063 | RTN | 24 | |
| 064 | RCLi | 36 45 | |
| 065 | RCL5 | 36 05 | |
| 066 | SF0 | 16 21 00 | |
| 067 | F1? | 16 23 01 | test for printorder |
| 068 | GTO6 | 22 06 | |
| 069 | CLX | -51 | |
| 070 | RCL4 | 36 04 | |
| 071 | CF0 | 16 22 00 | |
| 072 | *LBL6 | 21 06 | |
| 073 | GSB8 | 23 08 | calc & print elts. |
| 074 | GTO1 | 22 01 | |
| 075 | *LBL8 | 21 08 | calculate and print |
| 076 | × | -35 | subroutine for |
| 077 | STO8 | 35 08 | bandstop filters |
| 078 | F0? | 16 23 00 | |
| 079 | PRTX | -14 | |
| 080 | RCL0 | 36 00 | |
| 081 | $X^2$ | 53 | |
| 082 | × | -35 | |
| 083 | 1/X | 52 | |
| 084 | PRTX | -14 | |
| 085 | F0? | 16 23 00 | |
| 086 | GTO6 | 22 06 | |
| 087 | RCL8 | 36 08 | |
| 088 | PRTX | -14 | |
| 089 | *LBL6 | 21 06 | |
| 090 | SPC | 16-11 | |
| 091 | RTN | 24 | |
| 092 | *LBLa | 21 16 11 | lowpass type 1 |
| 093 | SPC | 16-11 | print heading |
| 094 | 3 | 03 | "31" |
| 095 | 1 | 01 | |
| 096 | PRTX | -14 | |
| 097 | SPC | 16-11 | |
| 098 | CF0 | 16 22 00 | |
| 099 | GSB7 | 23 07 | calculate consts |
| 100 | GTO2 | 22 02 | goto output rout. |

REGISTERS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 $2\pi f_c$ | 1 $2\pi BW$ | 2 R | 3 | 4 used | 5 used | 6 n | 7 k | 8 | 9 |
| S0 $a_n$ | S1 $a_{n-1}$ | S2 $a_{n-2}$ | S3 $a_{n-3}$ | S4 $a_{n-4}$ | S5 $a_{n-5}$ | S6 $a_{n-6}$ | S7 $a_{n-7}$ | S8 $a_{n-8}$ | S9 $a_{n-9}$ |
| A $a_{n-10}$ | B $a_{n-11}$ | C $a_{n-12}$ | D | E | I index | | | | |

# 97 Program Listing II



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 101 | *LBLb | 21 16 12 | Lowpass Type 2 |
| 102 | SPC | 16-11 | print headings |
| 103 | 3 | 03 | |
| 104 | 2 | 02 | "32" |
| 105 | PRTX | -14 | |
| 106 | SPC | 16-11 | |
| 107 | CF0 | 16 22 00 | lowpass filter |
| 108 | GSB7 | 23 07 | change to type 2 |
| 109 | RCL2 | 36 02 | coefficients |
| 110 | $X^2$ | 53 | |
| 111 | ST÷4 | 35-24 04 | |
| 112 | STx5 | 35-35 05 | |
| 113 | GTO2 | 22 02 | goto output routine |
| 114 | *LBLd | 21 16 14 | Highpass Type 2 |
| 115 | SPC | 16-11 | print heading |
| 116 | 4 | 04 | |
| 117 | 2 | 02 | "42" |
| 118 | PRTX | -14 | |
| 119 | SPC | 16-11 | |
| 120 | SF0 | 16 21 00 | highpass filter |
| 121 | GSB7 | 23 07 | calc coeff's |
| 122 | GTO2 | 22 02 | goto output routine |
| 123 | *LBLc | 21 16 13 | Highpass Type 1 |
| 124 | SPC | 16-11 | print heading |
| 125 | 4 | 04 | |
| 126 | 1 | 01 | "41" |
| 127 | PRTX | -14 | |
| 128 | SPC | 16-11 | |
| 129 | SF0 | 16 21 00 | highpass filter |
| 130 | GSB7 | 23 07 | calc coeff's |
| 131 | RCL2 | 36 02 | |
| 132 | $X^2$ | 53 | |
| 133 | ST÷4 | 35-24 04 | |
| 134 | STx5 | 35-35 05 | |
| 135 | *LBL2 | 21 02 | lopass/hipass out. |
| 136 | GSB9 | 23 09 | increment k |
| 137 | X≤Y? | 16-35 | test for loop exit |
| 138 | RTN | 24 | |
| 139 | RCLi | 36 45 | recall $a_k$ |
| 140 | F0? | 16 23 00 | highpass? |
| 141 | 1/X | 52 | if so form $1/a_k$ |
| 142 | RCL5 | 36 05 | scale element value |
| 143 | x | -35 | |
| 144 | PRTX | -14 | print element |
| 145 | GSB9 | 23 09 | increment k |
| 146 | X≤Y? | 16-35 | test for loop exit |
| 147 | RTN | 24 | |
| 148 | RCLi | 36 45 | recall $a_k$ |
| 149 | F0? | 16 23 00 | highpass? |
| 150 | 1/X | 52 | if so form $1/a_k$ |
| 151 | RCL4 | 36 04 | scale element value |
| 152 | x | -35 | |
| 153 | PRTX | -14 | print element |
| 154 | GTO2 | 22 02 | loop |
| 155 | *LBL7 | 21 07 | type 1 routine |
| 156 | RCL2 | 36 02 | R |
| 157 | RCL1 | 36 01 | 2πBW |
| 158 | ÷ | -24 | |
| 159 | STO4 | 35 04 | inductor scaling |
| 160 | RCL2 | 36 02 | |
| 161 | $X^2$ | 53 | |
| 162 | ÷ | -24 | |
| 163 | STO5 | 35 05 | capacitor scaling |
| 164 | 0 | 00 | initialize k |
| 165 | STO7 | 35 07 | |
| 166 | RTN | 24 | |
| 167 | *LBL9 | 21 09 | increment k and |
| 168 | 1 | 01 | test loop exit |
| 169 | ST+7 | 35-55 07 | |
| 170 | RCL7 | 36 07 | |
| 171 | 9 | 09 | |
| 172 | + | -55 | |
| 173 | STOI | 35 46 | |
| 174 | RCL7 | 36 07 | |
| 175 | RCL6 | 36 06 | |
| 176 | 1 | 01 | |
| 177 | + | -55 | |
| 178 | RTN | 24 | |

| | | |
|---|---|---|
| 200 | | |
| 210 | | |
| 220 | | |

| LABELS | | | | | FLAGS | SET STATUS |
|---|---|---|---|---|---|---|
| A Store $\omega_0 = 2\pi f_0 \to R_1$ | B Store $2\pi BW \to R_1$ | C Store $R \to R_2$ | D Bandstop type 1 | E Bandstop Type 2 | 0 used | |
| a Lowpass Type 1 | b Lowpass Type 2 | c Highpass Type 1 | d Highpass Type 2 | e | 1 used | |
| 0 Bandstop coef calc | 1 Bandstop loop destin. | 2 Lopass/Hipass loop return | 3 | 4 | 2 | |
| 5 | 6 local loop destination | 7 Hi/Low pass coefficients | 8 Bandstop output routine | 9 increment k and test exit | 3 | |

| FLAGS | ON | OFF |
|---|---|---|
| 0 | ☐ | ■ |
| 1 | ☐ | ■ |
| 2 | ☐ | ■ |
| 3 | ☐ | ■ |

| TRIG | |
|---|---|
| DEG | ■ |
| GRAD | ☐ |
| RAD | ☐ |

| DISP | |
|---|---|
| FIX | ☐ |
| SCI | ☐ |
| ENG | ■ |
| n | 3 |

# Program Description I

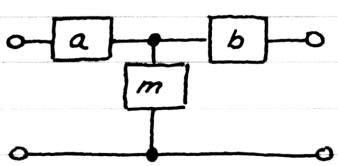
**Program Title** Y-Δ TRANSFORM FOR L,R, or C

**Contributor's Name** BRUCE K. MURDOCK
**Address** 6875 SABADO TARDE RD.
**City** GOLETA **State** CALIF **Zip Code** 93017

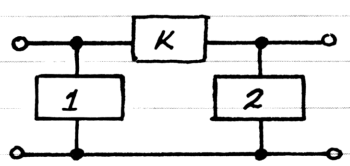
**Program Description, Equations, Variables** This program performs the Y-Δ transform for trios of resistors, inductors, or capacitors. These transformations find use wherever awkward or physically impractical element values result from electrical network design. The resistive transform is oftentimes used with op-amp summing network design to keep the resistor values low. The inductive and capacitive transforms can be of assistance in filter design, and form part of the set of filter design programs contained herein.

The Y-Δ transforms for one-of-a-kind elements are summarized below.

"Y" topology




"Δ" topology




for Capacitors:

$Y \Rightarrow \Delta$

$C_1 = C_a C_m / \Sigma C$

$C_2 = C_b C_m / \Sigma C$

$C_k = C_a C_b / \Sigma C$

$\Sigma C = C_a + C_b + C_m$

$\Delta \rightarrow Y$

$C_a = \Sigma CC / C_2$

$C_b = \Sigma CC / C_1$

$C_m = \Sigma CC / C_K$

$\Sigma CC = C_1 C_2 + C_2 C_K + C_1 C_K$

for Inductors (and Resistors, replace L's by R's)

$Y \Rightarrow \Delta$

$L_1 = \Sigma LL / L_b$

$L_2 = \Sigma LL / L_a$

$L_K = \Sigma LL / L_m$

$\Sigma LL = L_a L_b + L_b L_m + L_a L_m$

$\Delta \Rightarrow Y$

$L_a = L_1 L_K / \Sigma L$

$L_b = L_2 L_K / \Sigma L$

$L_m = L_1 L_2 / \Sigma L$

$\Sigma L = L_1 + L_2 + L_K$

This program has been verified only with respect to the numerical example given in *Program Description II.* User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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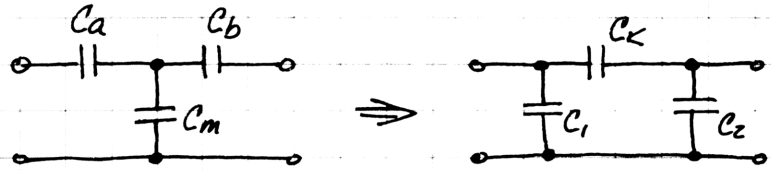
# Program Description II

**Sketch(es)** Convert the following Capacitor networks




**Sample Problem(s)** for $C_a = 1\mu F$, $C_b = 3\mu F$, and $C_2 = 2\mu F$ perform the Y->Δ transform and find $C_1$, $C_2$, and $C_K$. Compute the total capacitance both before and after the transformation.

$\Sigma C$ before xfm = $6\mu F$

**Solution(s)** Enter data into program 1E-6 [A], 2E-6 [B], 3E-6 [C], elements are capacitors [f] [A]. to list input elements [f] [E]. To perform Y->Δ transform [D]*. To list transformed elements [f] [E]. The transformed element values are: $C_1 = 0.333^{-}\mu F$, $C_K = 0.5\mu F$, $C_2 = 1.00\mu F$, and $\Sigma C's = 1.833\cdots\mu F$. The total capacity has been reduced by 69.4 %!

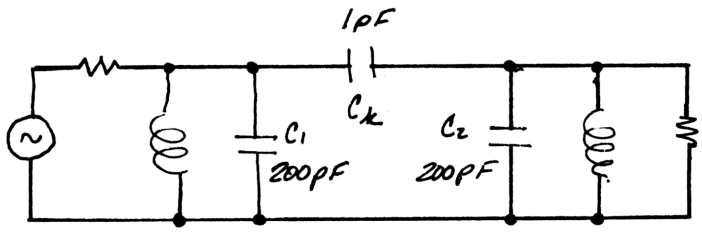
**Reference(s)** Weinberg, Louis; Network analysis and Synthesis; Wiley

* [D] calls [f] [E] both before and after transformation. [f] [E] lists the currently stored element values.

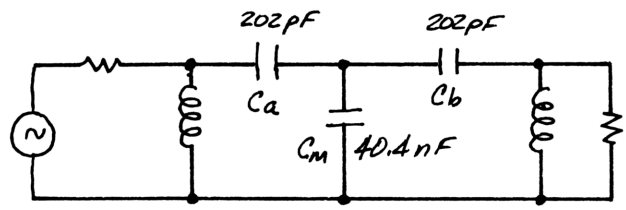
# Program Description I

A MORE PRACTICAL TRANSFORMATION EXAMPLE:

A TOP COUPLED PARALLEL RESONANT BANDPASS FILTER HAS BEEN DESIGNED USING THE TYPE 7 FILTER PROGRAM. THE ELEMENT VALUES ARE SHOWN:




THE 1 PICOFARAD COUPLING CAPACITOR IS TROUBLESOME AS IT IS THE SAME RELATIVE VALUE AS PRINTED CIRCUIT BOARD PARASITIC CAPACITIES. THE ABOVE DELTA OF CAPACITORS MAY BE TRANSFORMED INTO A WYE CONFIGURATION TO OBTAIN A BETTER SELECTION OF ELEMENT VALUES.




```
          ENG
          DSP3
  200.-12 GSBA
          GSBC
    1.-12 GSBB
          GSBD
          GSBE

200.0-12  ***  C1
1.000-12  ***  Ck
200.0-12  ***  C2
401.0-12  ***  ZC
```

DATA ENTRY

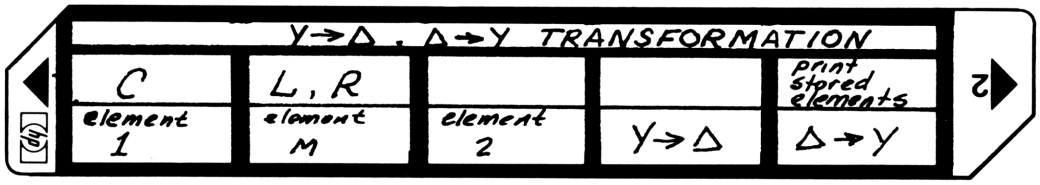
Δ→Y xfm

```
202.0-12  ***  Ca
40.40-09  ***  CM
202.0-12  ***  Cb
40.80-09  ***  ZC'S
```

WITH THE TRANSFORMED NETWORK IN THE CIRCUIT, NO CAPACITOR IS SMALLER THAN 202 pF, AND PARASITIC BOARD CAPACITY IS EASILY MANAGED.

# User Instructions






| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1 | LOAD PROGRAM | | | | |
| | | | | | |
| 2 | SELECT ELEMENT TYPE | | | | |
| | a) IF CAPACITORS | | f | A | |
| | b) IF INDUCTORS OR RESISTORS | | f | B | |
| | | | | | |
| 3 | LOAD ELEMENTS Y or Δ | | | | |
| | a) LOAD ELEMENT a or 1 | | A | | |
| | b) LOAD ELEMENT m or k | | B | | |
| | c) LOAD ELEMENT b or 2 | | C | | |
| | | | | | |
| 4 | OBTAIN TRANSFORMED ELEMENTS | | | | |
| | a) Y→Δ TRANSFORMATION | | D | | ELEMENT a |
| | | | | | " m |
| | | | | | " b |
| | | | | | Σ a, m, b |
| | | | | | |
| | | | | | ELEMENT 1 |
| | | | | | " k |
| | | | | | " 2 |
| | | | | | Σ 1, k, 2 |
| | | | | | |
| | b) Δ→Y TRANSFORMATION | | E | | ELEMENT 1 |
| | | | | | " k |
| | | | | | " 2 |
| | | | | | Σ 1, k, 2 |
| | | | | | |
| | | | | | ELEMENT a |
| | | | | | " m |
| | | | | | " b |
| | | | | | Σ a, m, b |
| | | | | | |
| 5 | TO PRINT PRESENTLY STORED | | | | |
| | ELEMENTS | | f | E | ELEMENT 1, a |
| | | | | | " k, m |
| | | | | | " 2, b |
| | | | | | Σ ELEMENTS |
| | | | | | |
| | | | | | |

# Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| | | | DATA ENTRY |
| 001 | *LBLA | 21 11 | ENTER ELEMENT 1 or a |
| 002 | STOA | 35 11 | |
| 003 | RTN | 24 | |
| 004 | *LBLB | 21 12 | ENTER ELEMENT k or m |
| 005 | STOB | 35 12 | |
| 006 | RTN | 24 | |
| 007 | *LBLC | 21 13 | ENTER ELEMENT 2 or b |
| 008 | STOC | 35 13 | |
| 009 | RTN | 24 | |
| 010 | *LBLa | 21 16 11 | CLEAR FLAG 0 TO INDICATE CAPACITORS |
| 011 | CF0 | 16 22 00 | |
| 012 | RTN | 24 | |
| 013 | *LBLb | 21 16 12 | SET FLAG 0 TO INDICATE RESISTORS OR INDUCTORS |
| 014 | SF0 | 16 21 00 | |
| 015 | RTN | 24 | |
| 016 | *LBLe | 21 16 15 | PRINT STORED ELEMENTS AND SUM OF STORED ELEMENTS |
| 017 | SPC | 16-11 | |
| 018 | RCLA | 36 11 | |
| 019 | PRTX | -14 | |
| 020 | RCLB | 36 12 | |
| 021 | PRTX | -14 | |
| 022 | + | -55 | |
| 023 | RCLC | 36 13 | |
| 024 | PRTX | -14 | |
| 025 | + | -55 | |
| 026 | PRTX | -14 | |
| 027 | SPC | 16-11 | |
| 028 | RTN | 24 | |
| 029 | *LBLD | 21 14 | Y→Δ ROUTINE FOR CAPACITORS OR Δ→Y ROUTING FOR RESISTORS AND INDUCTORS |
| 030 | GSBe | 23 16 15 | |
| 031 | F0? | 16 23 00 | |
| 032 | GTO0 | 22 00 | |
| 033 | *LBL1 | 21 01 | |
| 034 | RCLA | 36 11 | |
| 035 | RCLB | 36 12 | |
| 036 | + | -55 | |
| 037 | RCLC | 36 13 | |
| 038 | + | -55 | |
| 039 | STOD | 35 14 | |
| 040 | RCLA | 36 11 | |
| 041 | RCLB | 36 12 | |
| 042 | × | -35 | |
| 043 | RCLD | 36 14 | |
| 044 | ÷ | -24 | |
| 045 | STOE | 35 15 | |
| 046 | RCLA | 36 11 | |
| 047 | RCLC | 36 13 | |
| 048 | × | -35 | |
| 049 | RCLD | 36 14 | |
| 050 | ÷ | -24 | |
| 051 | RCLE | 36 15 | |
| 052 | STOA | 35 11 | |
| 053 | R↓ | -31 | |
| 054 | STOE | 35 15 | |
| 055 | RCLB | 36 12 | |
| 056 | RCLC | 36 13 | |
| 057 | × | -35 | |
| 058 | RCLD | 36 14 | |
| 059 | ÷ | -24 | |
| 060 | STOC | 35 13 | |
| 061 | RCLE | 36 15 | |
| 062 | STOB | 35 12 | |
| 063 | GTOe | 22 16 15 | |

**REGISTERS**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| ELEMENT 1 or a | ELEMENT k or m | ELEMENT 2 or b | Σ X or ΣXX X = L, R or C | used | |

# Program Listing II



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 064 | *LBLE | 21 15 | Δ -> Y TRANSFORM |
| 065 | GSBe | 23 16 15 | FOR CAPACITORS |
| 066 | F0? | 16 23 00 | OR |
| 067 | GTO1 | 22 01 | |
| 068 | *LBL0 | 21 00 | Y -> Δ TRANSFORM |
| 069 | RCLA | 36 11 | FOR RESISTORS |
| 070 | RCLB | 36 12 | AND INDUCTORS |
| 071 | × | -35 | |
| 072 | RCLB | 36 12 | |
| 073 | RCLC | 36 13 | |
| 074 | × | -35 | |
| 075 | + | -55 | |
| 076 | RCLA | 36 11 | |
| 077 | RCLC | 36 13 | |
| 078 | × | -35 | |
| 079 | + | -55 | |
| 080 | STOD | 35 14 | |
| 081 | RCLC | 36 13 | |
| 082 | ÷ | -24 | |
| 083 | STOE | 35 15 | |
| 084 | RCLD | 36 14 | |
| 085 | RCLB | 36 12 | |
| 086 | ÷ | -24 | |
| 087 | STOB | 35 12 | |
| 088 | RCLD | 36 14 | |
| 089 | RCLA | 36 11 | |
| 090 | ÷ | -24 | |
| 091 | STOC | 35 13 | |
| 092 | RCLE | 36 15 | |
| 093 | STOA | 35 11 | |
| 094 | GTOe | 22 16 15 | |

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| | | | |

| LABELS | | | | | FLAGS | SET STATUS | | |
|---|---|---|---|---|---|---|---|---|
| A ELEMENT 1 or a ENTRY | B ELEMENT 2 or M ENTRY | C ELEMENT 2 or b ENTRY | D Y -> Δ xfm | E Δ -> Y xfm | 0 "0" = CAP "1" = L or R | FLAGS | TRIG | DISP |
| a set CAPACITOR | b set INDUCTOR OR RESISTOR | c | d | e PRINT ELEMENTS | 1 | ON OFF<br>0 ■ □<br>1 □ ■<br>2 □ ■<br>3 □ ■ | DEG ■<br>GRAD □<br>RAD □ | FIX ■<br>SCI □<br>ENG □<br>n 5 |
| 0 L or R DESTINATION | 1 L or R DESTINATION | 2 | 3 | 4 | 2 | | | |
| 5 | 6 | 7 | 8 | 9 | 3 | | | |

# Program Description I

**Program Title** CHEBYCHEV ACTIVE LOWPASS FILTER DESIGN AND POLE LOCATIONS

**Contributor's Name** Bruce K. Murdock

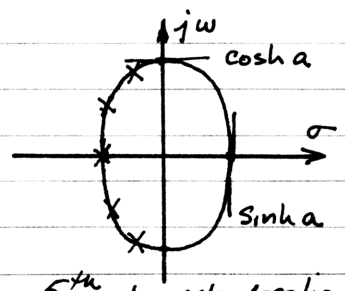
**Address** 6875 Sabado Tarde Road

**City** Goleta **State** Calif **Zip Code** 93017

**Program Description, Equations, Variables** This program calculates the un-normalized Chebychev lowpass active filter values for the Sallen and Key circuit, and also calculates the locations of the real, and complex conjugate pole locations which are used as input for other active filter realizations such as the Delyiannis resonator circuit. If the filter order is odd, a second card is required to obtain the last conjugate pair and real pole location.

The pole locations of a normalized Chebychev lowpass filter lie on an ellipse whose major axis dimension is cosh(a), and whose minor axis dimension is sinh(a), where $a = \frac{1}{n} \operatorname{arcsinh} \frac{1}{\epsilon}$. Epsilon is related to the passband ripple in dB by the expression $\epsilon = \left\{ 10^{0.1\,\epsilon_{dB}} - 1 \right\}^{1/2}$.

Using these quantities, the real and imaginary parts of the pole locations are calculated.




5th order pole locations

pole locations:

real part, $\sigma_k = (\sinh a)\left(\sin \frac{2k-1}{2n}\pi\right)$

imaginary part, $\omega_k = (\cosh a)\left(\cos \frac{2k-1}{2n}\pi\right)$

$k = 1, 2, 3, \cdots, n$

**Operating Limits and Warnings** This type of filter synthesis is called the cascade method. Each pole pair is synthesized by an isolated op-amp resonator circuit. The entire filter is formed from a cascade of such resonator circuits. With each pole pair being independant the overall filter sensitivities to component value changes are higher than an equivalent L-C filter, hence, high order filters (n greater than 9 or so) are quite difficult to tune, and high component precision is required. The leapfrog active topology is one solution here.

This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning the program material.

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# Program Description I

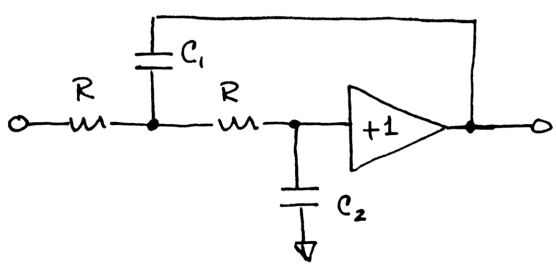
Each pole pair location may be expressed in terms of real and imaginary parts which is the Cartesian coordinate system, or the polar coordinate system may be used, in which case the pole pair location may be expressed by a natural frequency, $w_n$, and a Q, or quality factor. The relation between these reference systems is:

$$\omega_n = \sqrt{\sigma_k^2 + \omega_k^2}$$

$$\theta = \arctan \frac{\omega_k}{\sigma_k}$$

$$Q = \frac{1}{2\cos\theta}$$

The element values of the Sallen and Key type op-amp resonator are easily expressed in terms of $w_n$ and Q as follows:



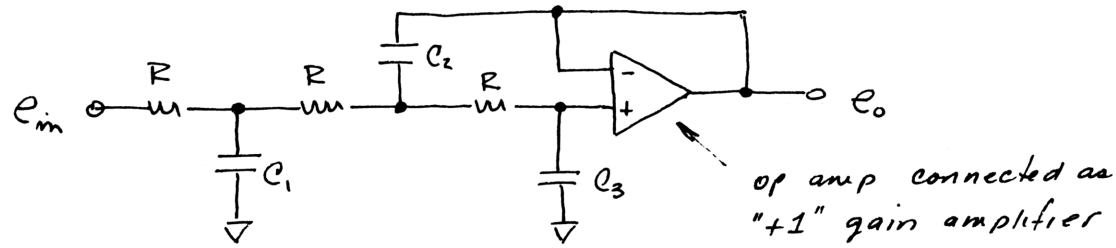

$$C_1 = \frac{2Q}{\omega_n R} \quad ; \quad C_2 = \frac{C_1}{4Q^2}$$

This program uses these relationships derived above to sequentially increment k, find the normalized pole pair location, find the associated natural frequency and Q, and then to calculate the two capacitor values. The filter is denormalized by multipling the normalized natural frequency by the filter cutoff frequency or by an additional multiplication of cosh(1/n(arccosh(1/e))) depending whether the filter is to be $e_{dB}$ or 3dB down at the cutoff frequency.

If the filter order is odd, then a real pole also exists. A third order op-amp resonator circuit may be employed to produce this pole and one complex conjugate pole pair also. The lowest Q pole pair is generally chosen in this instance to keep the element value spread within bounds.

# Program Description I

3rd Order filter section




$$e_o/e_{in} = \frac{1}{Cs^3 + Bs^2 + As + 1} = \underbrace{\frac{1}{\frac{s^2}{\omega_n^2} + \frac{s}{\omega_n Q} + 1}}_{\text{second order pole pair}} \cdot \underbrace{\frac{1}{\tau s + 1}}_{\text{real pole}}$$

$$A = C_1 + 3C_3 = \tau + \frac{1}{\omega_n Q}$$

$$B = 2C_3(C_1 + C_2) = \frac{\tau}{\omega_n Q} + \frac{1}{\omega_n^2}$$

$$C = C_1 C_2 C_3 = \tau/\omega_n^2$$

These equations may be solved to find $C_1$, $C_2$, and $C_3$ after algebraic manipulation, a cubic equation in $C_2$ alone is obtained.

$$C_2^3(4C - 2AB) + C_2^2(4AC + 3B^2) + C_2(-12BC) + 12C^2 = 0$$

The closed form cubic solution from the Rubber handbook math tables is used to find $C_2$.

$$p = \frac{4AC + 3B^2}{4C - 2AB} = (D \text{ in program listing})$$

$$q = \frac{-12BC}{4C - 2AB}$$

$$r = \frac{12C^2}{4C - 2AB}$$

# Program Description I

$$a = \frac{1}{9}\left\{3q - p^2\right\}$$

$$b = \frac{1}{2}\left\{\frac{p}{27}\left(9q - 2p^2\right) - r\right\}$$

$$C_2 = \left\{b + \sqrt{b^2 + a^3}\right\}^{1/3} + \left\{b - \sqrt{b^2 + a^3}\right\}^{1/3} - \frac{p}{3}$$

once $C_2$ is obtained, the other capacitor values follow

$$C_1 = \frac{2C \cdot C_2}{BC_2 - 2C}$$

and

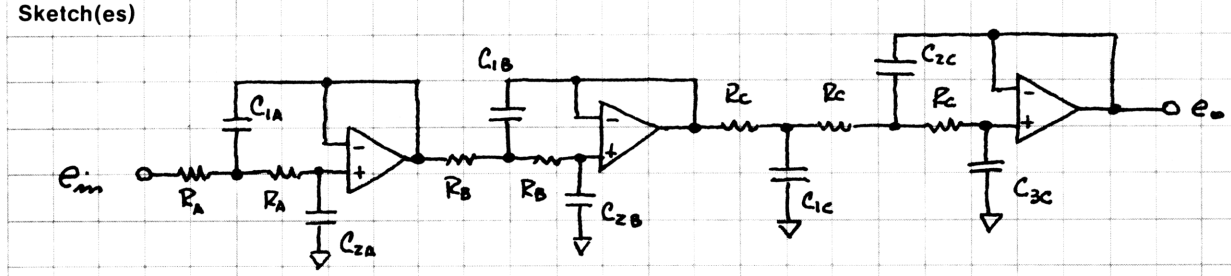
$$C_3 = \frac{C}{C_1 C_2}$$

the second card of this program solves the above cubic equation and algebra to obtain $C_1$, $C_2$, and $C_3$.

A Newton-Raphson, or Wegstein iterative type solution could be used to solve the cubic with less program coding, however, a second card is necessary in either case and the direct solution method executes faster.

# Program Description II

**Sketch(es)**




**Sample Problem(s)**

A 1dB ripple Chebychev lowpass filter must pass all frequencies between DC and 1000 Hz within 1dB, and reject all frequencies higher than 2000 Hz by at least 60 dB. The Kawakami nomographs, ~~fo~~ the Butterworth and Chebychev Filter Order Calculation program may be used to determine the necessary filter order. The program calculates a minimum order of 6.28, which is rounded to the nearest higher integer, 7. A 7th order, 1 dB ripple Chebychev will be 68.2 dB down at $\lambda = 2000/1000 = 2$ .

This program will be used to find the element values for a 7th order, 1 dB ripple, 1000 Hz cutoff Chebychev lowpass filter.

**Solution(s)** The program output is shown on the next page. An impedance level of 10000 Ohms is chosen. As can be seen from the printout, this value results in a reasonable selection of capacitor values, the smallest being 732 pF, and the largest being .1611 uF. One should be careful to keep the minimum capacity value at least several hundred picofarads to minimize the effect of parasitic capacity.

**Reference(s)**

# Program Description

```
    1. GSBA   ripple in dB
    7. GSBB   filter order
 1.+04 GSBC   resistance level, ohms = RA = RB = RC
 1000. GSBE   freq where filter is εdB (1dB) down
first resonator (second order)
6.26014+03  ***   ωn
10.8987+00  ***   Q
348.192-09  ***   C1A
732.846-12  ***   C2A
second resonator (second order)
5.07911+03  ***   ωn
3.15586+00  ***   Q
124.268-09  ***   C1B
3.11935-09  ***   C2B
third resonator (third order)
3.01626+03  ***   ωn } second order pole pair
1.29693+00  ***   Q
1.29066+03  ***   σ  ← load second card here & press [A]
84.2120-09  ***   C1C
161.111-09  ***   C2C
6.27702-09  ***   C3C
```

# User Instructions

Chebychev Active L.P. Filters & Pole locations, CARD #1

| | | | | |
|---|---|---|---|---|
| $\epsilon_{dB}$ | filter order, n | resistance R | $f_{-3dB}$ and start | $f_{-\epsilon dB}$ and start |

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1. | LOAD PROGRAM | | | | |
| 2 | KEY IN PASSBAND RIPPLE IN dB | $\epsilon_{dB}$ | | A | |
| 3 | KEY IN FILTER ORDER | n | | B | |
| 4 | KEY IN DE-NORMALIZATION RESISTANCE | R | | C | |
| 5 | START PROGRAM EXECUTION | | | | |
| | a) IF FILTER IS TO BE -3dB DOWN AT CUTOFF FREQUENCY | $f_{CUTOFF}$ | | D | SEE E |
| | b) IF FILTER IS TO BE $-\epsilon dB$ DOWN AT CUTOFF FREQUENCY | $f_{CUTOFF}$ | | E | $\omega_{n1}$ |
| | | | | | $Q_1$ |
| | | | | | $C_{11}$ |
| | | | | | $C_{21}$ |
| | | | | | $\omega_{n2}$ |
| | | | | | $Q_2$ |
| | | | | | $C_{12}$ |
| | | | | | $C_{22}$ |
| | | | | | ⋮ |
| | * IF FILTER ORDER IS ODD, ..... WILL BE DISPLAYED WHICH SIGNALS THE OPERATOR TO LOAD THE SECOND CARD AND PRESS [A] | | EVEN ORDER | | ..... * |
| | | | | | ⋮ |
| | | | | | $\omega_{An}$ |
| | | | | | $Q_n$ |
| | | | | | $C_{1n}$ |
| | | | | | $C_{2n}$ |
| | | | ODD ORDER | | $\omega_{An}$ |
| | | | | | $Q_n$ |
| | | | | | $\sigma_n$ |
| | | | | | $C_{1n}$ |
| | | | | | $C_{2n}$ |
| | | | | | $C_{3n}$ |

# User Instructions

Chebychev Active L.P. Filters & Pole locations
CARD #2 (FOR 3rd order section)

START

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|---|---|---|---|---|---|
| 1 | LOAD PROGRAM | | | | |
| | | | | | |
| 2 | SWITCH TO "MAN" MODE TO | | | | |
| | SUPPRESS KEYSTROKE PRINTOUT | | | | |
| | | | | | |
| 3 | CONTINUE PROGRAM EXECUTION | | | A | $C_1$ |
| | | | | | $C_2$ |
| | | | | | $Q_3$ |

# Program Listing I



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | $\epsilon_{dB}$ |
| 002 | F2? | 16 23 02 | |
| 003 | P⇄S | 16-51 | |
| 004 | STOB | 35 12 | |
| 005 | RTN | 24 | |
| 006 | *LBLB | 21 12 | $n$ |
| 007 | F2? | 16 23 02 | |
| 008 | P⇄S | 16-51 | |
| 009 | STOA | 35 11 | |
| 010 | 2 | 02 | |
| 011 | ÷ | -24 | |
| 012 | ENT↑ | -21 | |
| 013 | INT | 16 34 | |
| 014 | CF0 | 16 22 00 | |
| 015 | X=Y? | 16-33 | |
| 016 | SF0 | 16 21 00 | |
| 017 | *LBL4 | 21 04 | |
| 018 | RCLA | 36 11 | |
| 019 | 2 | 02 | |
| 020 | × | -35 | |
| 021 | 1/X | 52 | |
| 022 | Pi | 16-24 | |
| 023 | × | -35 | |
| 024 | STOE | 35 15 | $\pi/2n$ |
| 025 | RCLB | 36 12 | |
| 026 | 1 | 01 | |
| 027 | 0 | 00 | |
| 028 | ÷ | -24 | |
| 029 | $10^x$ | 16 33 | |
| 030 | 1 | 01 | |
| 031 | - | -45 | |
| 032 | √X | 54 | $\epsilon$ |
| 033 | 1/X | 52 | |
| 034 | STO5 | 35 05 | |
| 035 | ENT↑ | -21 | |
| 036 | $X^2$ | 53 | |
| 037 | 1 | 01 | |
| 038 | + | -55 | |
| 039 | √X | 54 | |
| 040 | + | -55 | |
| 041 | LN | 32 | |
| 042 | RCLA | 36 11 | |
| 043 | ÷ | -24 | |
| 044 | $e^x$ | 33 | $a$ |
| 045 | STO2 | 35 02 | |
| 046 | ENT↑ | -21 | |
| 047 | 1/X | 52 | |
| 048 | - | -45 | |
| 049 | 2 | 02 | |
| 050 | ÷ | -24 | |
| 051 | STOC | 35 13 | $\sinh a$ |
| 052 | RCL2 | 36 02 | |
| 053 | ENT↑ | -21 | |
| 054 | 1/X | 52 | |
| 055 | + | -55 | |
| 056 | 2 | 02 | |
| 057 | ÷ | -24 | |
| 058 | STOD | 35 14 | $\cosh a$ |
| 059 | RTN | 24 | |
| 060 | *LBLC | 21 13 | $R$ level |
| 061 | F2? | 16 23 02 | |
| 062 | P⇄S | 16-51 | |
| 063 | STO6 | 35 06 | |
| 064 | RTN | 24 | |
| 065 | *LBLD | 21 14 | $f_{-3dB}$ & start |
| 066 | Pi | 16-24 | |
| 067 | 2 | 02 | |
| 068 | × | -35 | |
| 069 | × | -35 | |
| 070 | F3? | 16 23 03 | |
| 071 | STO9 | 35 09 | $\omega_{-3dB}$ |
| 072 | F2? | 16 23 02 | |
| 073 | P⇄S | 16-51 | |
| 074 | RCL5 | 36 05 | |
| 075 | ENT↑ | -21 | |
| 076 | $X^2$ | 53 | |
| 077 | 1 | 01 | |
| 078 | - | -45 | |
| 079 | √X | 54 | |
| 080 | + | -55 | |
| 081 | LN | 32 | |
| 082 | RCLA | 36 11 | |
| 083 | ÷ | -24 | |
| 084 | $e^x$ | 33 | |
| 085 | ENT↑ | -21 | |
| 086 | 1/X | 52 | |
| 087 | + | -55 | |
| 088 | 2 | 02 | |
| 089 | ÷ | -24 | $\cosh\left(\frac{1}{n}\cosh^{-1}\frac{1}{\epsilon}\right)$ |
| 090 | 1/X | 52 | |
| 091 | RCL9 | 36 09 | |
| 092 | × | -35 | |
| 093 | STO3 | 35 03 | $\omega_{-\epsilon dB}$ |
| 094 | 1 | 01 | |
| 095 | STO0 | 35 00 | initialize $2k-1=1$ |
| 096 | GTO1 | 22 01 | |
| 097 | *LBLE | 21 15 | $f_{-\epsilon dB}$ and start |
| 098 | Pi | 16-24 | |
| 099 | 2 | 02 | |
| 100 | × | -35 | |
| 101 | × | -35 | |
| 102 | F3? | 16 23 03 | |
| 103 | STO3 | 35 03 | $\omega_{-\epsilon dB}$ |
| 104 | F2? | 16 23 02 | |
| 105 | P⇄S | 16-51 | |
| 106 | SPC | 16-11 | |
| 107 | 1 | 01 | |
| 108 | STO0 | 35 00 | initialize $2k-1=1$ |

**REGISTERS**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $2k-1$ | $2Q$ | $a$ or $\omega_n$ | $1$ or $\omega_{-3dB}$ | | $1/\epsilon$ | $R$ | $\omega_k$ | $\sigma_k$ | used |
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| $n$ | $\epsilon_{dB}$ | $\sinh a$ | $\cosh a$ | $\pi/2n$ | |

# 97 Program Listing II

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 109 | *LBL1 | 21 01 | |
| 110 | SPC | 16-11 | |
| 111 | RCL0 | 36 00 | |
| 112 | RCLE | 36 15 | |
| 113 | × | -35 | |
| 114 | STO1 | 35 01 | |
| 115 | COS | 42 | |
| 116 | RCLD | 36 14 | |
| 117 | × | -35 | |
| 118 | STO7 | 35 07 | |
| 119 | RCL1 | 36 01 | |
| 120 | SIN | 41 | |
| 121 | RCLC | 36 13 | |
| 122 | × | -35 | |
| 123 | STO8 | 35 08 | |
| 124 | →P | 34 | |
| 125 | RCL3 | 36 03 | |
| 126 | × | -35 | |
| 127 | PRTX | -14 | $\omega_n$ |
| 128 | STO2 | 35 02 | |
| 129 | X⇄Y | -41 | |
| 130 | COS | 42 | |
| 131 | 1/X | 52 | |
| 132 | STO1 | 35 01 | |
| 133 | 2 | 02 | |
| 134 | ÷ | -24 | |
| 135 | PRTX | -14 | Q |
| 136 | 2 | 02 | |
| 137 | ST+0 | 35-55 00 | increment k |
| 138 | F0? | 16 23 00 | filter even? |
| 139 | GTO3 | 22 03 | |
| 140 | RCL0 | 36 00 | |
| 141 | 1 | 01 | |
| 142 | + | -55 | |
| 143 | RCLA | 36 11 | |
| 144 | X≤Y? | 16-35 | last section? |
| 145 | GTO2 | 22 02 | |
| 146 | *LBL3 | 21 03 | |
| 147 | RCL1 | 36 01 | |
| 148 | RCL2 | 36 02 | |
| 149 | ÷ | -24 | |
| 150 | RCL6 | 36 06 | |
| 151 | ÷ | -24 | |
| 152 | PRTX | -14 | $C_1$ |
| 153 | RCL1 | 36 01 | |
| 154 | X² | 53 | |
| 155 | ÷ | -24 | |
| 156 | PRTX | -14 | $C_2$ |
| 157 | RCL0 | 36 00 | |
| 158 | RCLA | 36 11 | |
| 159 | X>Y? | 16-34 | not last section? |
| 160 | GTO1 | 22 01 | |
| 161 | SPC | 16-11 | |
| 162 | SPC | 16-11 | |
| 163 | RTN | 24 | |
| 164 | *LBL2 | 21 02 | |
| 165 | RCLC | 36 13 | |
| 166 | RCL3 | 36 03 | |
| 167 | × | -35 | |
| 168 | PRTX | -14 | real pole location |
| 169 | 9 | 09 | display .111111111 |
| 170 | 1/X | 52 | |
| 171 | RTN | 24 | (means load second card) |

| LABELS | | | | | FLAGS |
|---|---|---|---|---|---|
| A ENTER $\epsilon_{dB}$ | B ENTER n | C ENTER R | D $f_{-3dB}$ start | E $f_{-6dB}$ start | 0 n even |
| a | b | c | d | e | 1 |
| 0 | 1 $\omega_n$ & Q calc | 2 odd order output | 3 even order output | 4 | 2 P25 used. add # times |
| 5 | 6 | 7 | 8 | 9 | 3 |

| SET STATUS | | |
|---|---|---|
| FLAGS (ON / OFF) | TRIG | DISP |
| 0 ☐ ■ | DEG ☐ | FIX ☐ |
| 1 ☐ ■ | GRAD ☐ | SCI ☐ |
| 2 ☐ ■ | RAD ■ | ENG ■ |
| 3 ☐ ■ | | n 5 |

# Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 001 | *LBLA | 21 11 | START |
| 002 | F2? | 16 23 02 | |
| 003 | P⇄S | 16-51 | |
| 004 | RCL7 | 36 07 | |
| 005 | RCL8 | 36 08 | |
| 006 | P⇄S | 16-51 | |
| 007 | SF2 | 16 21 02 | |
| 008 | STO0 | 35 00 | |
| 009 | X² | 53 | |
| 010 | X⇄Y | -41 | |
| 011 | X² | 53 | |
| 012 | + | -55 | |
| 013 | STO1 | 35 01 | |
| 014 | 2 | 02 | |
| 015 | ST×0 | 35-35 00 | |
| 016 | RCLC | 36 13 | |
| 017 | RCL1 | 36 01 | |
| 018 | × | -35 | |
| 019 | 1/X | 52 | |
| 020 | STO2 | 35 02 | "C" |
| 021 | RCLC | 36 13 | |
| 022 | RCL0 | 36 00 | |
| 023 | + | -55 | |
| 024 | × | -35 | |
| 025 | STO3 | 35 03 | "B" |
| 026 | RCLC | 36 13 | |
| 027 | RCL0 | 36 00 | |
| 028 | × | -35 | |
| 029 | RCL1 | 36 01 | |
| 030 | + | -55 | |
| 031 | RCL2 | 36 02 | |
| 032 | × | -35 | |
| 033 | STO4 | 35 04 | "A" |
| 034 | RCL2 | 36 02 | |
| 035 | 4 | 04 | |
| 036 | × | -35 | |
| 037 | RCL4 | 36 04 | |
| 038 | RCL3 | 36 03 | |
| 039 | × | -35 | |
| 040 | 2 | 02 | |
| 041 | × | -35 | |
| 042 | - | -45 | |
| 043 | STO5 | 35 05 | "D" |
| 044 | RCL2 | 36 02 | |
| 045 | 4 | 04 | |
| 046 | × | -35 | |
| 047 | RCL4 | 36 04 | |
| 048 | × | -35 | |
| 049 | RCL3 | 36 03 | |
| 050 | X² | 53 | |
| 051 | 3 | 03 | |
| 052 | × | -35 | |
| 053 | + | -55 | |
| 054 | RCL5 | 36 05 | |
| 055 | ÷ | -24 | |
| 056 | STO6 | 35 06 | "p" |
| 057 | 1 | 01 | |
| 058 | 2 | 02 | |
| 059 | RCL2 | 36 02 | |
| 060 | X² | 53 | |
| 061 | × | -35 | |
| 062 | RCL5 | 36 05 | |
| 063 | ÷ | -24 | |
| 064 | STO8 | 35 08 | "r" |
| 065 | CHS | -22 | |
| 066 | RCL3 | 36 03 | |
| 067 | × | -35 | |
| 068 | RCL2 | 36 02 | |
| 069 | ÷ | -24 | |
| 070 | STO7 | 35 07 | "q" |
| 071 | RCL7 | 36 07 | |
| 072 | 3 | 03 | |
| 073 | × | -35 | |
| 074 | RCL6 | 36 06 | |
| 075 | X² | 53 | |
| 076 | - | -45 | |
| 077 | 9 | 09 | |
| 078 | ÷ | -24 | |
| 079 | STO0 | 35 00 | "a" |
| 080 | RCL6 | 36 06 | |
| 081 | X² | 53 | |
| 082 | 2 | 02 | |
| 083 | × | -35 | |
| 084 | RCL7 | 36 07 | |
| 085 | 9 | 09 | |
| 086 | × | -35 | |
| 087 | - | -45 | |
| 088 | RCL6 | 36 06 | |
| 089 | × | -35 | |
| 090 | 2 | 02 | |
| 091 | 7 | 07 | |
| 092 | ÷ | -24 | |
| 093 | RCL8 | 36 08 | |
| 094 | + | -55 | |
| 095 | 2 | 02 | |
| 096 | ÷ | -24 | |
| 097 | STO1 | 35 01 | "b" |
| 098 | X² | 53 | |
| 099 | RCL0 | 36 00 | |
| 100 | 3 | 03 | |
| 101 | Y^X | 31 | |
| 102 | + | -55 | |
| 103 | √X | 54 | |
| 104 | STO9 | 35 09 | $\sqrt{(b^2+a^3)}$ |
| 105 | RCL1 | 36 01 | |
| 106 | - | -45 | |
| 107 | 3 | 03 | |
| 108 | 1/X | 52 | |
| 109 | Y^X | 31 | |
| 110 | RCL1 | 36 01 | |

## REGISTERS

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $w_k$ | $\sigma_k$ | |
| S0 $a, C_1$ | S1 $b$ | S2 $C$ | S3 $B$ | S4 $A$ | S5 $D=4C-2AB$ | S6 $p$ | S7 $q$ | S8 $r$ | S9 $C_2$ |

| A | B | C | D | E | I |
|---|---|---|---|---|---|
| | | Sinha | | | |

# 97 Program Listing II



| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 111 | RCL9 | 36 09 | |
| 112 | + | -55 | |
| 113 | CHS | -22 | |
| 114 | 3 | 03 | |
| 115 | 1/X | 52 | |
| 116 | Y^X | 31 | |
| 117 | + | -55 | |
| 118 | RCL6 | 36 06 | |
| 119 | 3 | 03 | |
| 120 | ÷ | -24 | |
| 121 | - | -45 | |
| 122 | STO9 | 35 09 | $C_2$ |
| 123 | 2 | 02 | |
| 124 | x | -35 | |
| 125 | RCL2 | 36 02 | |
| 126 | x | -35 | |
| 127 | RCL9 | 36 09 | |
| 128 | RCL3 | 36 03 | |
| 129 | x | -35 | |
| 130 | 2 | 02 | |
| 131 | RCL2 | 36 02 | |
| 132 | x | -35 | |
| 133 | - | -45 | |
| 134 | ÷ | -24 | |
| 135 | STO0 | 35 00 | $C_1$ |
| 136 | RCL9 | 36 09 | |
| 137 | x | -35 | |
| 138 | 1/X | 52 | |
| 139 | RCL2 | 36 02 | |
| 140 | x | -35 | $C_3$ |
| 141 | RCL9 | 36 09 | $C_2$ |
| 142 | RCL0 | 36 00 | $C_1$ |
| 143 | P⇄S | 16-51 | |
| 144 | CF2 | 16 22 02 | |
| 145 | GSB1 | 23 01 | |
| 146 | GSB1 | 23 01 | |
| 147 | GSB1 | 23 01 | |
| 148 | GTO2 | 22 02 | |
| 149 | *LBL1 | 21 01 | Impedance and |
| 150 | RCL3 | 36 03 | frequency denormalization |
| 151 | ÷ | -24 | subroutine |
| 152 | RCL6 | 36 06 | |
| 153 | ÷ | -24 | |
| 154 | PRTX | -14 | |
| 155 | R↓ | -31 | |
| 156 | RTN | 24 | |
| 157 | *LBL2 | 21 02 | |
| 158 | SPC | 16-11 | |
| 159 | SPC | 16-11 | |
| 160 | RTN | 24 | |

| STEP | KEY ENTRY | KEY CODE | COMMENTS |
|---|---|---|---|
| 170 | | | |
| 180 | | | |
| 190 | | | |
| 200 | | | |
| 210 | | | |
| 220 | | | |

| LABELS | | | | | FLAGS |
|---|---|---|---|---|---|
| A START | B | C | D | E | 0 |
| a | b | c | d | e | 1 |
| 0 | 1 output subroutine | 2 | 3 | 4 | 2 P2S odd # of times |
| 5 | 6 | 7 | 8 | 9 | 3 |

**SET STATUS**

| FLAGS | ON | OFF | TRIG | | DISP | |
|---|---|---|---|---|---|---|
| 0 | ☐ | ☐ | DEG | ☐ | FIX | ☐ |
| 1 | ☐ | ☐ | GRAD | ☐ | SCI | ☐ |
| 2 | ☐ | ■ | RAD | ■ | ENG | ■ |
| 3 | ☐ | ☐ | | | n 5 | |

## NOTES

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