

HEWLETT-PACKARD

HP-67/HP-97

Users' Library Solutions
Butterworth and Chebyshev Filters



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Program Description I

Program Title NORMALIZED LOWPASS TO BANDSTOP, LOWPASS, OR HIGHPASS
TRANSFORMATION
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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 $j\omega$, or $1/s$ by $-j/\omega$. 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, ω_0 , and the design bandwidth, ω_c . The transformation equation becomes:

$$s \Rightarrow Q_L \left\{ \frac{s}{\omega_0} + \frac{\omega_0}{s} \right\} \quad \text{where } Q_L = \frac{\omega_0}{\omega_c} = \frac{\text{center frequency}}{\text{bandwidth}}$$

When the transformation is applied to the Butterworth lowpass magnitude equation, and s is replaced by $j\omega$, the following results:

$$|A(\omega)|_{bp} = \left\{ 1 + \left(Q_L \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right) \right)^{2n} \right\}^{-1/2}$$

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 $j\omega$ becomes:

$$\omega \Rightarrow 1 / \left(Q_L \left\{ \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right\} \right)$$

The Butterworth equation for the lowpass magnitude response transforms thus:

$$|A(\omega)|_{bs} = \left\{ \frac{\left[Q_L \left\{ \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right\} \right]^2}{1 + \left[Q_L \left\{ \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right\} \right]^2} \right\}^{1/2}$$

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)

$$1 \text{ } \mu\text{Hy} \leq L \leq 1 \text{ Hy}$$

$$5 \text{ pF} \leq C \leq 1 \text{ } \mu\text{F}$$

Practical (P)

$$0.2 \text{ } \mu\text{Hy} \leq L \leq 10 \text{ Hy}$$

$$2 \text{ pF} \leq C \leq 10 \text{ } \mu\text{F}$$

Marginally practical (M)

$$50 \text{ nHy} \leq L \leq 100 \text{ Hy}$$

$$0.5 \text{ pF} \leq C \leq 500 \text{ } \mu\text{F}$$

Impractical (I)

All element values that lie outside the range of Marginal

i. e.,

$$L < 50 \text{ nHy}$$

$$L > 100 \text{ Hy}$$

$$C < .5 \text{ pF}$$

$$C > 500 \text{ } \mu\text{F}$$

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

Frequency,

$$f_o = 10 \text{ Hz implies: } 3 \text{ Hz} \leq f_o < 30 \text{ Hz}$$

$$f_o = 100 \text{ Hz implies: } 30 \text{ Hz} \leq f_o < 300 \text{ Hz}$$

$$f_o = 1 \text{ kHz implies: } 300 \text{ Hz} \leq f_o < 3 \text{ kHz}$$

$$f_o = 10 \text{ kHz implies: } 3 \text{ kHz} \leq f_o < 30 \text{ kHz}$$

$$f_o = 100 \text{ kHz implies: } 30 \text{ kHz} \leq f_o < 300 \text{ kHz}$$

$$f_o = 1 \text{ MHz implies: } 300 \text{ kHz} \leq f_o < 3 \text{ MHz}$$

$$f_o = 10 \text{ MHz implies: } 3 \text{ MHz} \leq f_o < 30 \text{ MHz}$$

$$f_o = 100 \text{ MHz implies: } 30 \text{ MHz} \leq f_o < 300 \text{ MHz}$$

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

Loaded Q (Q_L), for bandpass and bandstop,

$$Q_L = 5 \text{ implies: } 3 \leq Q_L < 10$$

$$Q_L = 15 \text{ implies: } 10 \leq Q_L < 30$$

$$Q_L = 50 \text{ implies: } 30 \leq Q_L \leq 100$$

Impedance Level (source and load resistances equal)

$$R = 3 \text{ Ohms implies: } 1 \leq R < 10 \text{ (power filters)}$$

$$R = 50 \text{ Ohms implies: } 10 \leq R < 150$$

$$R = 500 \text{ Ohms implies: } 150 \leq R < 2.5\text{k}$$

$$R = 10 \text{ kOhms implies: } 2.5\text{k} \leq R < 50\text{k}$$

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 $\lambda = 12 \text{ kHz} / 1 \text{ kHz} = 12$ and the λ 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. $A_s^2 - 1 = (A_p^2 - 1)\lambda^{2n}$. 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 A_s and A_p are the ratio equivalents of those quantities expressed in dB, i.e.

$$A_s^2 = 10^{(A_s(\text{dB}))/10} ; A_p^2 = 10^{(A_p(\text{dB}))/10}$$

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.

$$\lambda = \left\{ \frac{A_s^2 - 1}{A_p^2 - 1} \right\}^{1/2n} \quad \text{where} \quad \begin{aligned} A_s^2 &= 10^{(A_s(\text{dB}))/10} \\ A_p^2 &= 10^{(A_p(\text{dB}))/10} \\ n &= 4 \end{aligned}$$

$$\lambda = 1.183301, \text{ then}$$

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

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 GSB4
Butterworth → GSB4

| | | |
|----------------|----------|-----|
| a ₁ | 0.765367 | *** |
| a ₂ | 1.847759 | *** |
| a ₃ | 1.847759 | *** |
| a ₄ | 0.765367 | *** |

load this program

Bandwidth 1183.301 GSB2
Resistance 1000. GSB0
Lowpass form 1 → GSB4

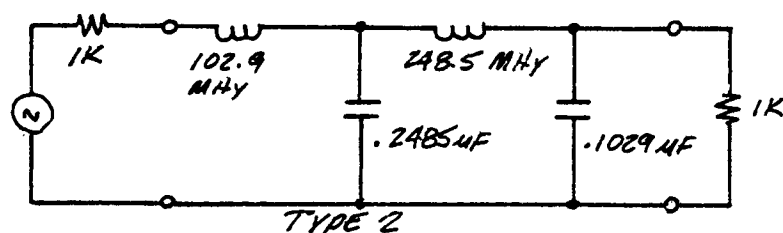
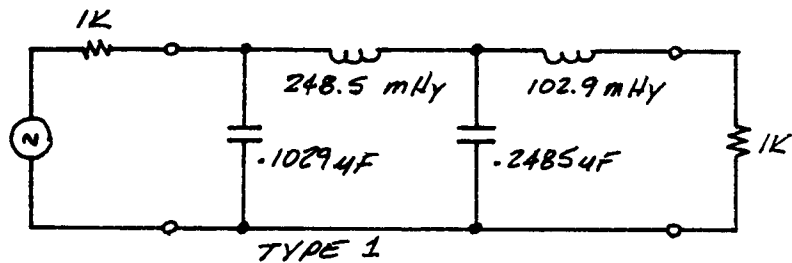
31.

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

Lowpass form 2 → GSB4

32.

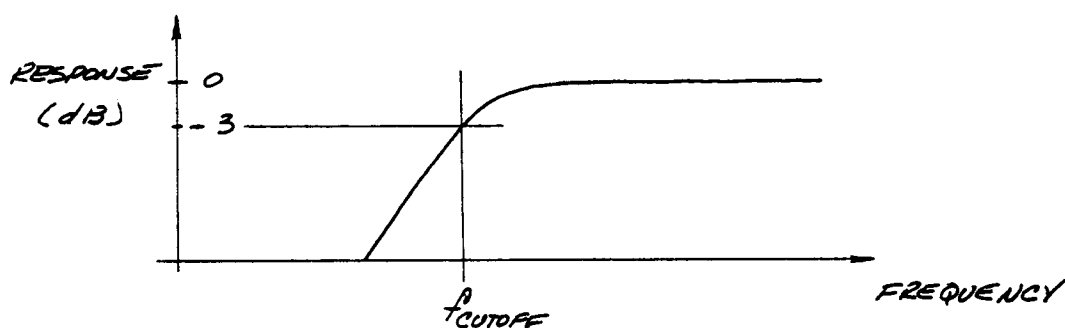
| | | |
|----|----------|-----|
| L1 | 102.9-03 | *** |
| C2 | 248.5-05 | *** |
| L3 | 248.5-03 | *** |
| C4 | 102.9-09 | *** |



Program Description

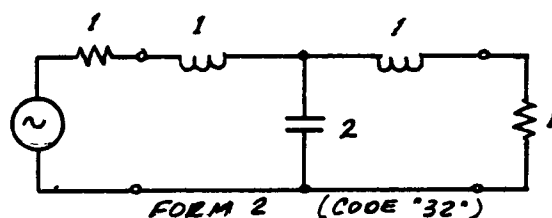
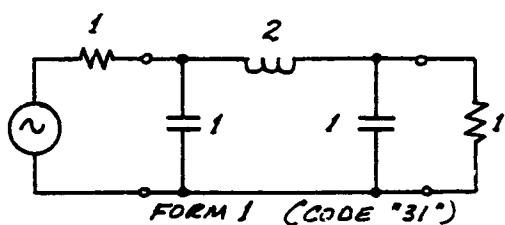
HIGHPASS FILTERS

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.

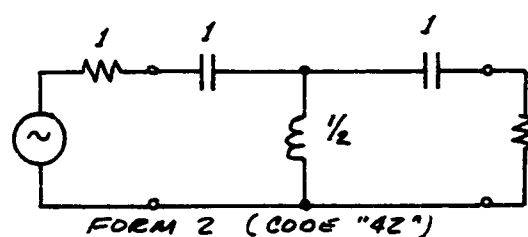
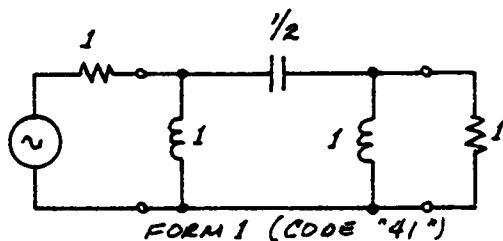


Conceptually the transformation is accomplished by replacing each capacitor with an inductor, and vice versa in the lowpass structure. The normalized highpass component values are the reciprocals of the normalized lowpass values.

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



The normalized highpass transforms are:



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.

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

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

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 $A_p=1$ dB, $A_s=60$ dB, 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 $\frac{1}{2}$ 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 $\lambda = 7.000000$ GSBA
 KEY IN $\epsilon_B = 1.000000$ GSBB
 $\omega_{-3dB} = 1.017285$ ***
 $G_1 = 2.166557$ ***
 $G_2 = 1.111509$ ***
 $G_3 = 3.093642$ ***
 $G_4 = 1.173521$ ***
 $G_5 = 3.093642$ ***
 $G_6 = 1.111509$ ***
 $G_7 = 2.166557$ ***

LOAD THIS PROGRAM

BANDWIDTH = 54.406 GSBB
 $R = 300.$ GSBC
 CALCULATE HIGHPASS "1" = GSBC

HIGHPASS "1" CODE 41.

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

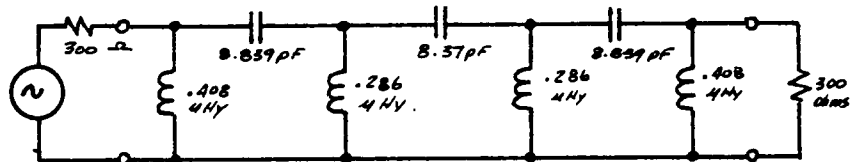
HIGHPASS "2" GSBC

CODE 42.

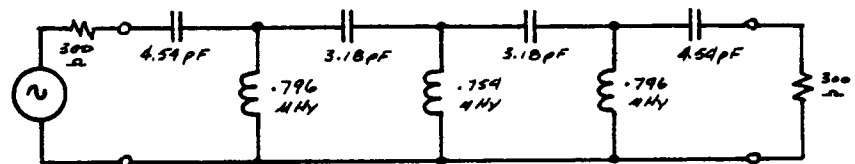
$C_1 = 4.535-12$ ***
 $L_2 = 795.5-09$ ***
 $C_3 = 3.176-12$ ***
 $L_4 = 753.5-09$ ***
 $C_5 = 3.176-12$ ***
 $L_6 = 795.5-09$ ***
 $C_7 = 4.535-12$ ***

SCHEMATICALLY, THE FILTERS ARE

1) UNBALANCED 300 OHM FILTERS:

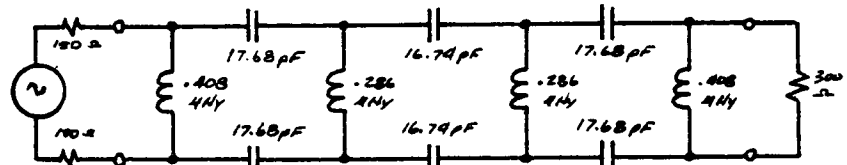


FORM 1

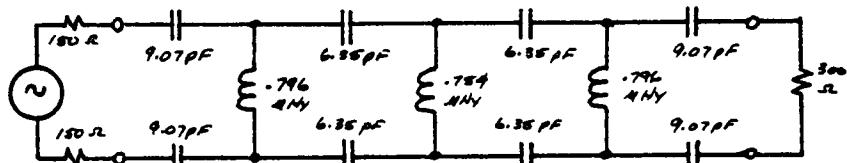


FORM 2

2) EQUIVALENT BALANCED FILTER FORMS



FORM 1



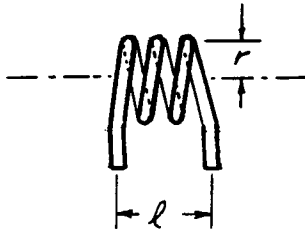
FORM 2

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.



$$L(\mu\text{Hy}) = \frac{r^2 n^2}{9r + 10l}$$

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

Wheeler's 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 independent 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:

$$n = \frac{5L(4Hy)}{r^2 p} \cdot \left\{ 1 + \sqrt{1 + \frac{.36 r^3 p^2}{L}} \right\}$$

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.

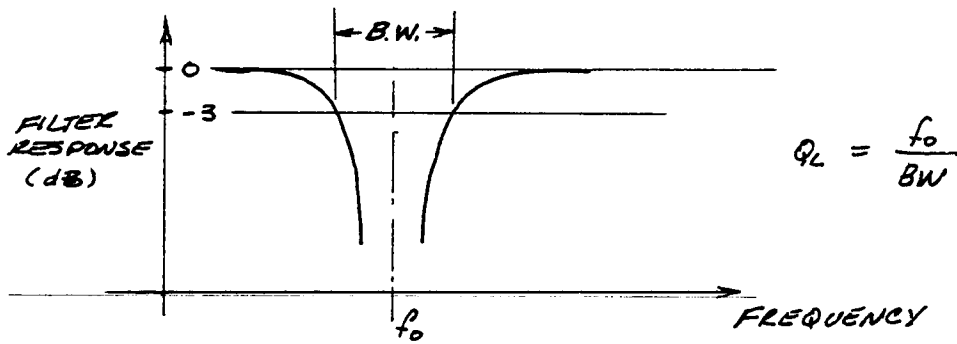
Program Description I

BANDSTOP TRANSFORMATION

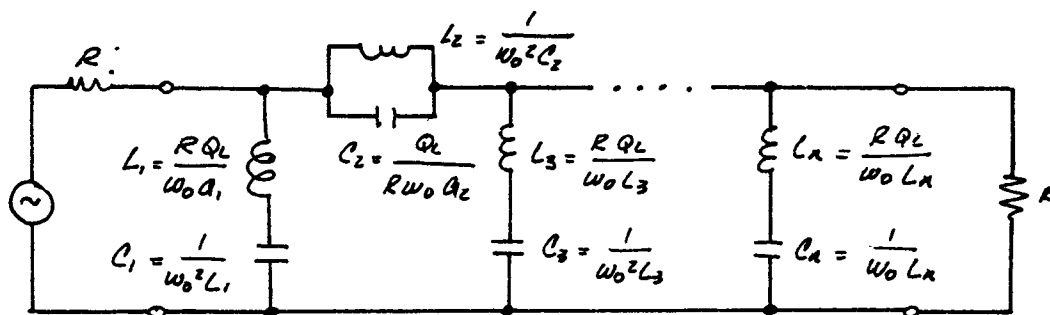
The bandstop filter transmits all frequencies except those lying within a given band of frequencies called the stopband. A subclass of this family of filters are sometimes called notch filters. A typical use of such a filter would be to remove interference, or unwanted signals from within a wanted spectrum. An example would be to place a notch filter in the antenna lead of a tv 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:



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

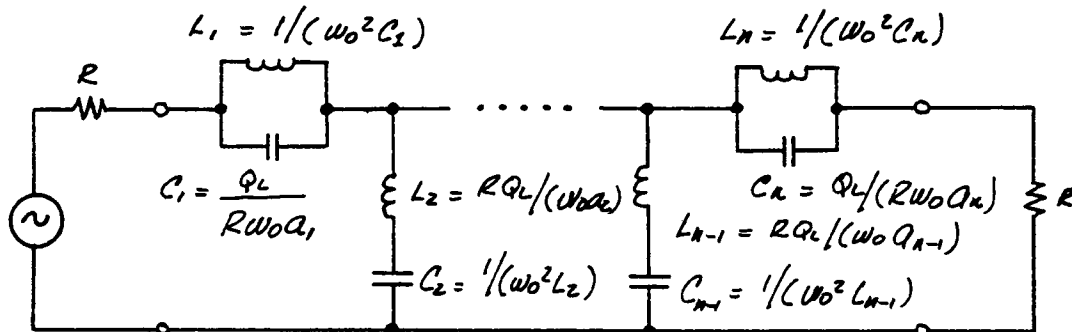


FORM 1 (odd order shown)
(heading "21")

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 $A_p = 1$ dB, $A_s = 20$ 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.

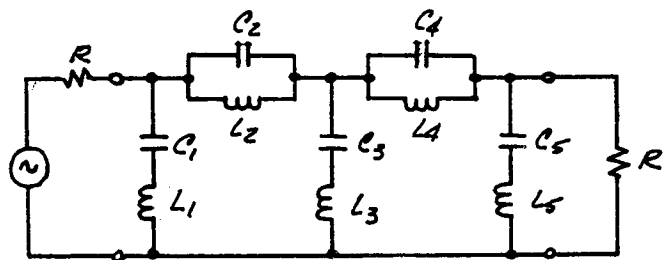
The HP-97 printout is shown on the next page for the above operations, and the two forms of the bandstop filter are shown schematically.

Program Description

LOADPASS: NARM CODE PROGRAM

INPUT $\begin{cases} N = 5.000000 \text{ GSBE} \\ GdB = 1.000000 \text{ GSBE} \\ W-3dB = 1.033615 \text{ ***} \end{cases}$

$\begin{matrix} G_1 & 2.134882 & *** \\ G_2 & 1.091107 & *** \\ G_3 & 3.000923 & *** \\ G_4 & 1.091107 & *** \\ G_5 & 2.134882 & *** \end{matrix}$



FORM 1

LOAD BANDSTOP

TRANSFORMATION PROGRAM

(THIS PROGRAM)

Center Freq 63.400 GSBE
Bandwidth 6.400 GSBE
Termination Resis. 75. GSBE
Bandstop Form 1 GSBE

Bandstop 1 code "21."

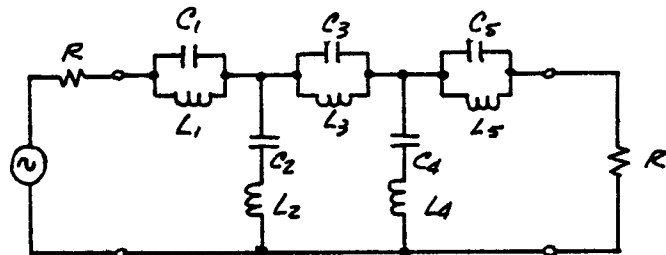
$\begin{matrix} C_1 = & 6.849-12 & *** \\ L_1 = & 931.9-09 & *** \end{matrix}$

$\begin{matrix} C_2 = & 324.1-12 & *** \\ L_2 = & 19.69-09 & *** \end{matrix}$

$\begin{matrix} C_3 = & 9.627-12 & *** \\ L_3 = & 662.9-09 & *** \end{matrix}$

$\begin{matrix} C_4 = & 324.1-12 & *** \\ L_4 = & 19.69-09 & *** \end{matrix}$

$\begin{matrix} C_5 = & 6.849-12 & *** \\ L_5 = & 931.9-09 & *** \end{matrix}$



FORM 2

In this particular example, form 2 is more physically realizable than is form 1. In form 1, $L_2 = 19.7 \text{ nHy}$ which parallel resonates with $C_2 = 324 \text{ pF}$. 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 $.6 \text{ inch}$ piece of straight #16 wire!

By contrast, L_1 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.

Bandstop Form 2 GSBE

Bandstop 2 code "22."

$\begin{matrix} C_1 = & 165.7-12 & *** \\ L_1 = & 38.52-09 & *** \end{matrix}$

$\begin{matrix} C_2 = & 3.500-12 & *** \\ L_2 = & 1.823-06 & *** \end{matrix}$

$\begin{matrix} C_3 = & 117.9-12 & *** \\ L_3 = & 54.15-09 & *** \end{matrix}$

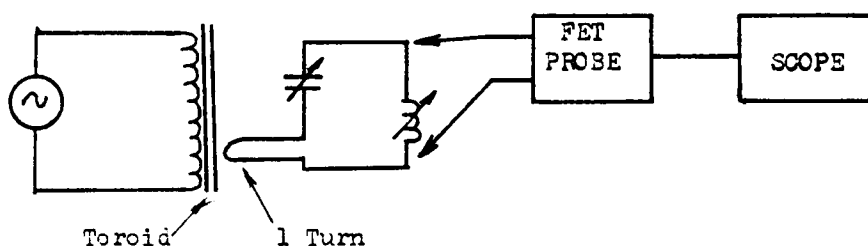
$\begin{matrix} C_4 = & 3.500-12 & *** \\ L_4 = & 1.823-06 & *** \end{matrix}$

$\begin{matrix} C_5 = & 165.7-12 & *** \\ L_5 = & 38.52-09 & *** \end{matrix}$

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 (certainly below 50 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 negligible 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 a 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 | |
| f_{center} | BW | R | Bandstop Type 1 | Bandstop Type 2 |

| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | | OUTPUT DATA/UNITS |
|------|---------------------------------|---------------------|----------------------|----------------------|-----------------------|
| 1 | LOAD PROGRAM | | <input type="text"/> | <input type="text"/> | |
| 2 | FOR LOWPASS COMPONENT VALUES | | <input type="text"/> | <input type="text"/> | |
| | a) LOAD BANDWIDTH (CUTOFF FREQ) | BW | <input type="text"/> | B | $2\pi BW$ |
| | b) LOAD RESISTANCE LEVEL | R | <input type="text"/> | C | R |
| | c) FOR TYPE 1 FILTER | | F | A | C_1 |
| | | | <input type="text"/> | <input type="text"/> | L_2 |
| | | | <input type="text"/> | <input type="text"/> | C_3 |
| | | | <input type="text"/> | <input type="text"/> | \vdots |
| | | | <input type="text"/> | <input type="text"/> | $C_n \text{ or } L_n$ |
| | d) FOR TYPE 2 FILTER | | A | B | L_1 |
| | | | <input type="text"/> | <input type="text"/> | C_2 |
| | | | <input type="text"/> | <input type="text"/> | L_3 |
| | | | <input type="text"/> | <input type="text"/> | \vdots |
| | | | <input type="text"/> | <input type="text"/> | $L_n \text{ or } C_n$ |
| 3 | FOR HIGHPASS COMPONENT VALUES | | <input type="text"/> | <input type="text"/> | |
| | a) LOAD CUTOFF FREQUENCY | f_{cutoff} | <input type="text"/> | B | $2\pi f_c$ |
| | b) LOAD RESISTANCE LEVEL | R | <input type="text"/> | C | R |
| | c) FOR TYPE 1 FILTER | | F | C | L_1 |
| | | | <input type="text"/> | <input type="text"/> | C_2 |
| | | | <input type="text"/> | <input type="text"/> | L_3 |
| | | | <input type="text"/> | <input type="text"/> | \vdots |
| | | | <input type="text"/> | <input type="text"/> | $C_n \text{ or } L_n$ |
| | d) FOR TYPE 2 FILTER | | F | D | C_1 |
| | | | <input type="text"/> | <input type="text"/> | L_2 |
| | | | <input type="text"/> | <input type="text"/> | C_3 |
| | | | <input type="text"/> | <input type="text"/> | \vdots |
| | | | <input type="text"/> | <input type="text"/> | $L_n \text{ or } C_n$ |

User Instructions

1 CONTINUED FROM PREVIOUS PAGE 2

[illegible]

97 Program Listing II

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| STEP | KEY ENTRY | KEY CODE | COMMENTS | STEP | KEY ENTRY | KEY CODE | COMMENTS |
|------|----------------|----------|-----------------------------|------|----------------|----------|-------------------|
| 101 | *LBL6 | 21 16 12 | Lowpass Type 2 | 155 | *LBL7 | 21 07 | type 1 routine |
| 102 | SPC | 16-11 | print headings | 156 | RCL2 | 36 02 | R |
| 103 | 3 | 03 | | 157 | RCL1 | 36 01 | 2 π BW |
| 104 | 2 | 02 | "32" | 158 | = | -24 | |
| 105 | PRTX | -14 | | 159 | ST04 | 35 04 | inductor scaling |
| 106 | SPC | 16-11 | | 160 | RCL2 | 36 02 | |
| 107 | CF0 | 16 22 00 | lowpass filter | 161 | X ² | 53 | |
| 108 | GSB7 | 23 07 | change to type 2 | 162 | = | -24 | |
| 109 | RCL2 | 36 02 | coefficients | 163 | ST05 | 35 05 | capacitor scaling |
| 110 | X ² | 53 | | 164 | 0 | 00 | initialize k |
| 111 | ST \div 4 | 35-24 04 | | 165 | ST07 | 35 07 | |
| 112 | ST \times 5 | 35-35 05 | | 166 | RTN | 24 | |
| 113 | GT02 | 22 02 | goto output routine | 167 | *LBL9 | 21 09 | increment k and |
| 114 | *LBL9 | 21 16 14 | Highpass Type 2 | 168 | 1 | 01 | test loop exit |
| 115 | SPC | 16-11 | print heading | 169 | ST+7 | 35-55 07 | |
| 116 | 4 | 04 | | 170 | RCL7 | 36 07 | |
| 117 | 2 | 02 | "42" | 171 | 9 | 09 | |
| 118 | PRTX | -14 | | 172 | + | -55 | |
| 119 | SPC | 16-11 | | 173 | ST01 | 35 46 | |
| 120 | SF0 | 16 21 00 | highpass filter | 174 | RCL7 | 36 07 | |
| 121 | GSB7 | 23 07 | calc coeff's | 175 | RCL6 | 36 06 | |
| 122 | GT02 | 22 02 | goto output routine | 176 | 1 | 01 | |
| 123 | *LBL6 | 21 16 13 | Highpass Type 1 | 177 | + | -55 | |
| 124 | SPC | 16-11 | print heading | 178 | RTN | 24 | |
| 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 \div 4 | 35-24 04 | | | | | |
| 134 | ST \times 5 | 35-35 05 | | | | | |
| 135 | *LBL2 | 21 02 | lopas/hipass out. | | | | |
| 136 | GSB9 | 23 09 | increment k | | | | |
| 137 | X \neq Y? | 16-35 | test for loop exit | | | | |
| 138 | RTN | 24 | | | | | |
| 139 | RCL1 | 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 \neq Y? | 16-35 | test for loop exit | | | | |
| 147 | RTN | 24 | | | | | |
| 148 | RCL1 | 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 | GT02 | 22 02 | loop | | | | |

| LABELS | | | | | FLAGS | SET STATUS | | |
|---|--|--------------------------------|------------------------------|--------------------------------|--------|--|---|---|
| A Store W0=2 π BW \rightarrow R0 | B Store 2 π BW \rightarrow R1 | C Store R \rightarrow R2 | D Bandstop Type 1 | E Bandstop Type 2 | 0 used | FLAGS | TRIG | DISP |
| a Lowpass Type 1 | b Lowpass Type 2 | c Highpass Type 1 | d Highpass Type 2 | e | 1 used | ON OFF | DEG <input checked="" type="checkbox"/> | FIX <input type="checkbox"/> |
| 0 Bandstop Loop calc | 1 Bandstop Loop destn. | 2 Lopass/Hipass Loop return | 3 | 4 | 2 | 0 <input type="checkbox"/> <input checked="" type="checkbox"/> | GRAD <input type="checkbox"/> | SCI <input type="checkbox"/> |
| 5 | 6 Local loop destination | 7 Hi/Low pass coefficients | 8 Bandstop output routine | 9 increment k and test exit | 3 | 1 <input type="checkbox"/> <input checked="" type="checkbox"/> | RAD <input type="checkbox"/> | ENG <input checked="" type="checkbox"/> |
| | | | | | | 2 <input type="checkbox"/> <input checked="" type="checkbox"/> | | n <u>3</u> |
| | | | | | | 3 <input type="checkbox"/> <input checked="" type="checkbox"/> | | |

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**

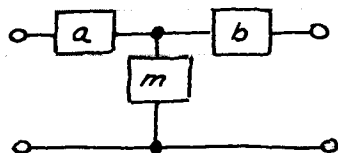
State **CALIF**

Zip Code **93017**

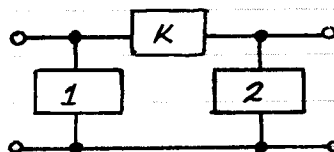
Program Description, Equations, Variables This program performs the Y-Δ transform for trios of resistors, inductors, or capacitors. These transformations find use wherever awkward or physically impractical element values result from electrical network design. The resistive transform is oftentimes used 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:

$$\begin{aligned}
 Y \Rightarrow \Delta \quad C_1 &= C_a C_m / \Sigma C \\
 C_2 &= C_b C_m / \Sigma C \\
 C_K &= C_a C_b / \Sigma C \\
 \Sigma C &= C_a + C_b + C_m
 \end{aligned}$$

$$\begin{aligned}
 \Delta \Rightarrow Y \quad C_a &= \Sigma C C / C_2 \\
 C_b &= \Sigma C C / C_1 \\
 C_m &= \Sigma C C / C_K \\
 \Sigma C C &= C_1 C_2 + C_2 C_K + C_1 C_K
 \end{aligned}$$

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

$$\begin{aligned}
 Y \Rightarrow \Delta \quad L_1 &= \Sigma L L / L_b \\
 L_2 &= \Sigma L L / L_a \\
 L_K &= \Sigma L L / L_m \\
 \Sigma L L &= L_a L_b + L_b L_m + L_a L_m
 \end{aligned}$$

$$\begin{aligned}
 \Delta \Rightarrow Y \quad L_a &= L_1 L_K / \Sigma L \\
 L_b &= L_2 L_K / \Sigma L \\
 L_m &= L_1 L_2 / \Sigma L \\
 \Sigma L &= L_1 + L_2 + L_K
 \end{aligned}$$

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.

NEITHER HP NOR THE CONTRIBUTOR MAKES ANY EXPRESS OR IMPLIED WARRANTY OF ANY KIND WITH REGARD TO THIS PROGRAM MATERIAL, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. NEITHER HP NOR THE CONTRIBUTOR SHALL BE LIABLE FOR INCIDENTAL OR CONSEQUENTIAL DAMAGES IN CONNECTION WITH OR ARISING OUT OF THE FURNISHING, USE OR PERFORMANCE OF THIS PROGRAM MATERIAL.

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 $C_m = 2 \mu F$ perform the $Y \rightarrow \Delta$ transform and find C_1 , C_2 , and C_k . Compute the total capacitance both before and after the transformation.

$$\Sigma C \text{ before xfm} = 6 \mu F$$

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 $Y \rightarrow \Delta$ 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 $\Sigma C's = 1.833 \mu F$. The total capacity has been reduced by 69.4%!

Reference(s)

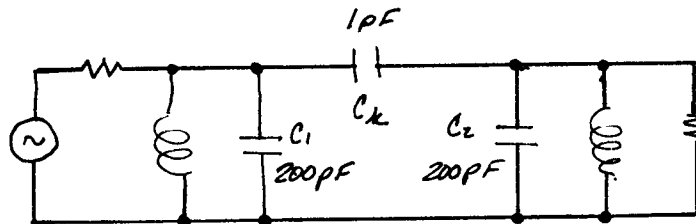
Weinberg, Louis; Network analysis and Synthesis; Wiley

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

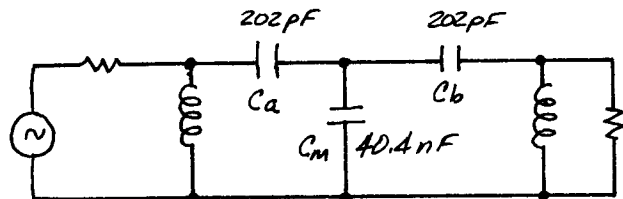
Program Description I

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 PICO FARAD 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 Y/YE CONFIGURATION TO OBTAIN A BETTER SELECTION OF ELEMENT VALUES.



| | | | |
|---------|------|---|---------------|
| ENG | | | |
| DSF3 | | | |
| 200.-12 | GSBA | } | DATA ENTRY |
| | GSBC | | |
| 1.-12 | GSBB | | |
| | GSB1 | | |
| | GSBE | | |

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

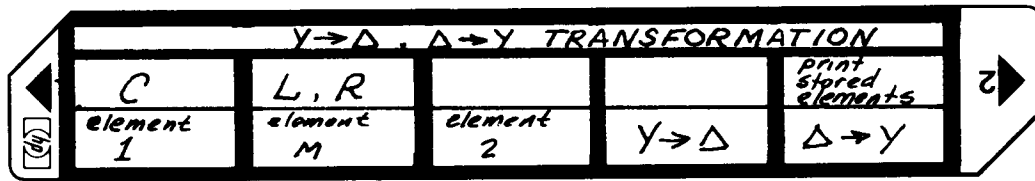
$\Delta \rightarrow Y$ xfm

| | | |
|----------|-----|------|
| 202.0-12 | *** | Ca |
| 40.40-09 | *** | Cm |
| 202.0-12 | *** | Cb |
| 40.60-09 | *** | 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

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| STEP | INSTRUCTIONS | INPUT DATA/UNITS | KEYS | OUTPUT DATA/UNITS |
|------|--|------------------|---|-------------------|
| 1 | LOAD PROGRAM | | <input type="text"/> <input type="text"/> | |
| 2 | SELECT ELEMENT TYPE | | <input type="text"/> <input type="text"/> | |
| | a) IF CAPACITORS | | f A | |
| | b) IF INDUCTORS OR RESISTORS | | f B | |
| 3 | LOAD ELEMENTS Y or Δ | | <input type="text"/> <input type="text"/> | |
| | a) LOAD ELEMENT a or 1 | | A <input type="text"/> | |
| | b) LOAD ELEMENT m or k | | B <input type="text"/> | |
| | c) LOAD ELEMENT b or 2 | | C <input type="text"/> | |
| 4 | OBTAIN TRANSFORMED ELEMENTS | | <input type="text"/> <input type="text"/> | |
| | a) $Y \rightarrow \Delta$ TRANSFORMATION | | D <input type="text"/> | ELEMENT a |
| | | | <input type="text"/> <input type="text"/> | " m |
| | | | <input type="text"/> <input type="text"/> | " b |
| | | | <input type="text"/> <input type="text"/> | $\Sigma a, m, b$ |
| | | | <input type="text"/> <input type="text"/> | |
| | | | <input type="text"/> <input type="text"/> | ELEMENT 1 |
| | | | <input type="text"/> <input type="text"/> | " k |
| | | | <input type="text"/> <input type="text"/> | " z |
| | | | <input type="text"/> <input type="text"/> | $\Sigma 1, k, z$ |
| | | | <input type="text"/> <input type="text"/> | |
| | b) $\Delta \rightarrow Y$ TRANSFORMATION | | E <input type="text"/> | ELEMENT 1 |
| | | | <input type="text"/> <input type="text"/> | " k |
| | | | <input type="text"/> <input type="text"/> | " z |
| | | | <input type="text"/> <input type="text"/> | $\Sigma 1, k, z$ |
| | | | <input type="text"/> <input type="text"/> | |
| | | | <input type="text"/> <input type="text"/> | ELEMENT a |
| | | | <input type="text"/> <input type="text"/> | " m |
| | | | <input type="text"/> <input type="text"/> | " b |
| | | | <input type="text"/> <input type="text"/> | $\Sigma a, m, b$ |
| | | | <input type="text"/> <input type="text"/> | |
| 5 | TO PRINT PRESENTLY STORED ELEMENTS | | f E | ELEMENT 1, a |
| | | | <input type="text"/> <input type="text"/> | " k, m |
| | | | <input type="text"/> <input type="text"/> | " z, b |
| | | | <input type="text"/> <input type="text"/> | Σ ELEMENTS |
| | | | <input type="text"/> <input type="text"/> | |
| | | | <input type="text"/> <input type="text"/> | |

Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS | STEP | KEY ENTRY | KEY CODE | COMMENTS | | |
|---------------------|---------------------|----------|---|------|-------------------------------|----------|--|----|----|
| DATA ENTRY | | | | | | | | | |
| 001 | *LBLA | 21 11 | ENTER ELEMENT 1 or a | 029 | *LBLD | 21 14 | Y→Δ ROUTINE FOR CAPACITORS OR Δ→Y ROUTING FOR RESISTORS AND INDUCTORS | | |
| 002 | STOA | 35 11 | | | | | | | |
| 003 | RTN | 24 | | | | | | | |
| 004 | *LBLB | 21 12 | ENTER ELEMENT k or m | 032 | GT00 | 22 00 | | | |
| 005 | STOB | 35 12 | | | | | | | |
| 006 | RTN | 24 | | | | | | | |
| 007 | *LBLC | 21 13 | ENTER ELEMENT 2 or b | 033 | *LBL1 | 21 01 | | | |
| 008 | STOC | 35 13 | | | | | | | |
| 009 | RTN | 24 | | | | | | | |
| 010 | *LBLd | 21 16 11 | CLEAR FLAG 0 TO INDICATE CAPACITORS | 034 | RCLA | 36 11 | | | |
| 011 | CF0 | 16 22 00 | | | | | | | |
| 012 | RTN | 24 | | | | | | | |
| 013 | *LBLb | 21 16 12 | SET FLAG 0 TO INDICATE RESISTORS OR INDUCTORS | 035 | RCLB | 36 12 | | | |
| 014 | SF0 | 16 21 00 | | | | | | | |
| 015 | RTN | 24 | | | | | | | |
| 016 | *LBLe | 21 16 15 | PRINT STORED ELEMENTS AND SUM OF STORED ELEMENTS | 036 | + | -55 | | | |
| 017 | SFC | 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 | | | | | | | |
| | | | | 037 | RCLC | 36 13 | | | |
| | | | | 038 | + | -55 | | | |
| | | | | 039 | STOD | 35 14 | | | |
| | | | | 040 | RCLA | 36 11 | | | |
| | | | | 041 | RCLB | 36 12 | | | |
| | | | | 042 | x | -35 | | | |
| | | | | 043 | RCLD | 36 14 | | | |
| | | | | 044 | = | -24 | | | |
| | | | | 045 | STOE | 35 15 | | | |
| | | | | 046 | RCLA | 36 11 | | | |
| | | | | 047 | RCLC | 36 13 | | | |
| | | | | 048 | x | -35 | | | |
| | | | | 049 | RCLD | 36 14 | | | |
| | | | | 050 | = | -24 | | | |
| | | | | 051 | RCLF | 36 15 | | | |
| | | | | 052 | STOA | 35 11 | | | |
| | | | | 053 | R↓ | -31 | | | |
| | | | | 054 | STOE | 35 15 | | | |
| | | | | 055 | RCLB | 36 12 | | | |
| | | | | 056 | RCLC | 36 13 | | | |
| | | | | 057 | x | -35 | | | |
| | | | | 058 | RCLD | 36 14 | | | |
| | | | | 059 | = | -24 | | | |
| | | | | 060 | STOC | 35 13 | | | |
| | | | | 061 | RCLF | 36 15 | | | |
| | | | | 062 | STOB | 35 12 | | | |
| | | | | 063 | GT0e | 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 ELEMENT 1 or a | B ELEMENT k or m | | C ELEMENT 2 or b | | D Σ X N Σ XX X = L, R or C | | E used | | I |

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[illegible]

Program Description I

Program Title CHEBYCHEV ACTIVE LOWPASS FILTER DESIGN AND POLE LOCATIONS

Contributor's Name Bruce K. Murdock

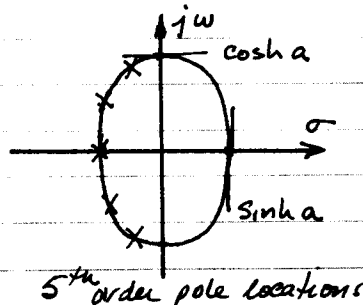
Address 6875 Sabado Tarde Road

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 $\epsilon = \left\{ 10^{0.1 \text{ dB}} - 1 \right\}^{1/2}$.

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



pole locations:

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

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

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

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 independent 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

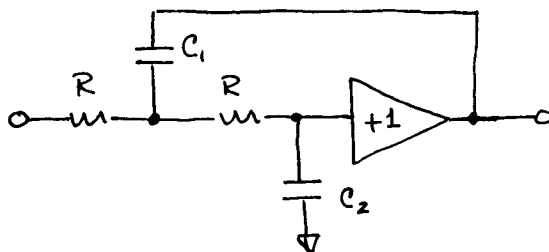
Each pole pair location may be expressed in terms of real and imaginary parts which is the Cartesian coordinate system, or the polar coordinate system may be used, in which case the pole pair location may be expressed by a natural frequency, ω_n , and a Q, or quality factor. The relation between these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



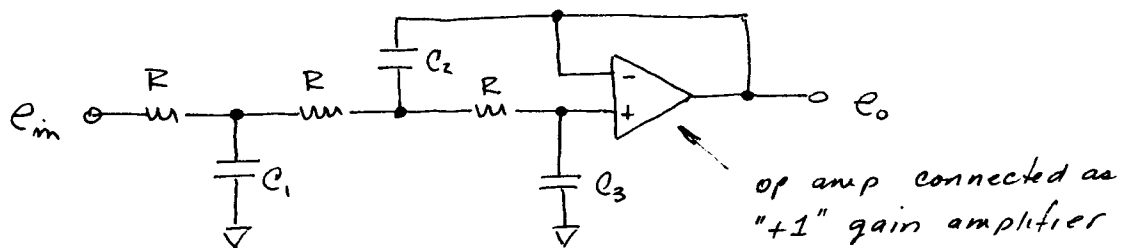
$$C_1 = \frac{2Q}{\omega_n R} \quad ; \quad C_2 = \frac{C_1}{4Q^2}$$

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 multiplying the normalized natural frequency by the filter cutoff frequency or by an additional multiplication of $\cosh(1/n(\operatorname{arccosh}(1/e)))$ 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



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

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

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

$$C = C_1 C_2 C_3 = \frac{1}{\omega_n^2}$$

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 .

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

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

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

Program Description I

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

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

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

once C_2 is obtained, the other capacitor values follow

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

and

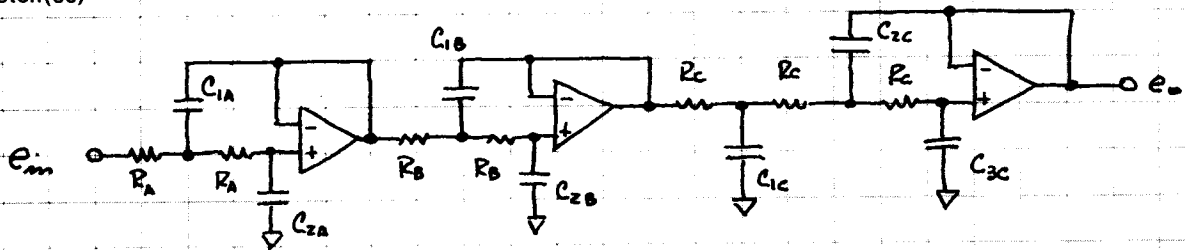
$$C_3 = \frac{C}{C_1 C_2}$$

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 Chebyshev 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, to the Butterworth and Chebyshev 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 Chebyshev 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 Chebyshev 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. GSBE filter order
 1.+04 GSBC resistance level, ohms = $R_A = R_B = R_C$
 1000. GSBE freq where filter is ϵ dB (1dB) down

first resonator (second order)

6.26014+03 *** ω_A
 10.8987+00 *** Q
 348.192-09 *** C_{1A}
 732.846-12 *** C_{2A}

second resonator (second order)

5.07911+03 *** ω_B
 3.15586+00 *** Q
 124.268-09 *** C_{1B}
 3.11935-09 *** C_{2B}

third resonator (third order)

3.01626+03 *** ω_C
 1.29693+00 *** Q } second order pole pair
 1.29066+03 *** $\frac{g}{C}$ }
 84.2120-09 *** C_{1C} } load second card here & press [A]
 161.111-09 *** C_{2C}
 6.27702-09 *** C_{3C}

User Instructions

| Chebyshev Active L.P. Filters & Pole Locations, CARD #1 | | | | |
|---|-------------------|----------------|----------------------|-------------------------------|
| ϵ_{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 | | <input type="text"/> | <input type="text"/> | |
| 2 | KEY IN PASSBAND RIPPLE IN dB | ϵ_{dB} | <input type="text"/> | A | |
| 3 | KEY IN FILTER ORDER | n | <input type="text"/> | B | |
| 4 | KEY IN DE-NORMALIZATION RESISTANCE | R | <input type="text"/> | C | |
| 5 | START PROGRAM EXECUTION | | <input type="text"/> | | |
| | a) IF FILTER IS TO BE -3dB DOWN AT CUTOFF FREQUENCY | f_{CUTOFF} | <input type="text"/> | D | SEE E |
| | b) IF FILTER IS TO BE - ϵ_{dB} DOWN AT CUTOFF FREQUENCY | f_{CUTOFF} | <input type="text"/> | E | ω_{n1} |
| | | | <input type="text"/> | | Q_1 |
| | | | <input type="text"/> | | C_{11} |
| | | | <input type="text"/> | | C_{21} |
| | | | <input type="text"/> | | |
| | | | <input type="text"/> | | ω_{n2} |
| | | | <input type="text"/> | | Q_2 |
| | | | <input type="text"/> | | C_{12} |
| | | | <input type="text"/> | | C_{22} |
| | | | <input type="text"/> | | ... |
| | | | <input type="text"/> | | ... |
| | * IF FILTER ORDER IS ODD, .IIIIIIIIII WILL BE DISPLAYED WHICH SIGNALS THE OPERATOR TO LOAD THE SECOND CARD AND PRESS [A] | | <input type="text"/> | | .IIIIIIIIII* |
| | | | <input type="text"/> | | ... |
| | | | <input type="text"/> | EVEN ORDER | ω_{n1} |
| | | | <input type="text"/> | | Q_n |
| | | | <input type="text"/> | | C_{1n} |
| | | | <input type="text"/> | | C_{2n} |
| | | | <input type="text"/> | | |
| | | | <input type="text"/> | ODD ORDER | ω_{n1} |
| | | | <input type="text"/> | | Q_n |
| | | | <input type="text"/> | | C_{1n} |
| | | | <input type="text"/> | | C_{2n} |
| | | | <input type="text"/> | | C_{3n} |

User Instructions

Chebyshev Active L.P. Filters & Pole Locations
CARD #2 (FOR 3rd order section)
START

[illegible]

| STEP | KEY ENTRY | KEY CODE | COMMENTS | STEP | KEY ENTRY | KEY CODE | COMMENTS |
|------|-----------------|----------|-----------------|------|----------------|----------|--|
| 001 | *LBLA | 21 11 | ϵ_{dB} | 056 | 2 | 02 | |
| 002 | F2? | 16 23 02 | | 057 | \div | -24 | |
| 003 | P2S | 16-51 | | 058 | ST00 | 35 14 | cosh a |
| 004 | ST06 | 35 12 | | 059 | RTN | 24 | |
| 005 | RTN | 24 | | | | | |
| 006 | *LBLB | 21 12 | n | 060 | *LBLC | 21 13 | R level |
| 007 | F2? | 16 23 02 | | 061 | F2? | 16 23 02 | |
| 008 | P2S | 16-51 | | 062 | P2S | 16-51 | |
| 009 | ST0A | 35 11 | | 063 | ST06 | 35 06 | |
| 010 | 2 | 02 | | 064 | RTN | 24 | |
| 011 | \div | -24 | | 065 | *LBLD | 21 14 | f -3dB & start |
| 012 | ENT1 | -21 | | 066 | Pi | 16-24 | |
| 013 | INT | 16 34 | | 067 | 2 | 02 | |
| 014 | CF0 | 16 22 00 | | 068 | x | -35 | |
| 015 | X=Y? | 16-33 | | 069 | x | -35 | |
| 016 | SF0 | 16 21 00 | | 070 | F3? | 16 23 03 | |
| 017 | *LBL4 | 21 04 | | 071 | ST09 | 35 09 | w -3dB |
| 018 | RCLA | 36 11 | | 072 | F2? | 16 23 02 | |
| 019 | 2 | 02 | | 073 | P2S | 16-51 | |
| 020 | x | -35 | | 074 | RCL5 | 36 05 | |
| 021 | 1/X | 52 | | 075 | ENT1 | -21 | |
| 022 | Pi | 16-24 | | 076 | X ² | 53 | |
| 023 | x | -35 | | 077 | 1 | 01 | |
| 024 | ST0E | 35 15 | $\pi/2n$ | 078 | - | -45 | |
| 025 | RCLB | 36 12 | | 079 | JX | 54 | |
| 026 | 1 | 01 | | 080 | + | -55 | |
| 027 | 0 | 00 | | 081 | LN | 32 | |
| 028 | \div | -24 | | 082 | RCLA | 36 11 | |
| 029 | 10 ^x | 16 33 | | 083 | \div | -24 | |
| 030 | 1 | 01 | | 084 | e ^x | 33 | |
| 031 | - | -45 | | 085 | ENT1 | -21 | |
| 032 | JX | 54 | ϵ | 086 | 1/X | 52 | |
| 033 | 1/X | 52 | | 087 | + | -55 | |
| 034 | ST05 | 35 05 | | 088 | 2 | 02 | |
| 035 | ENT1 | -21 | | 089 | \div | -24 | $\cosh(\frac{1}{n} \cosh^{-1} \frac{1}{\epsilon})$ |
| 036 | X ² | 53 | | 090 | 1/X | 52 | |
| 037 | 1 | 01 | | 091 | RCL9 | 36 09 | |
| 038 | + | -55 | | 092 | x | -35 | w - ϵ_{dB} |
| 039 | JX | 54 | | 093 | ST03 | 35 03 | |
| 040 | + | -55 | | 094 | 1 | 01 | |
| 041 | LN | 32 | | 095 | ST00 | 35 00 | initialize $2k-1 = 1$ |
| 042 | RCLA | 36 11 | | 096 | GT01 | 22 01 | |
| 043 | \div | -24 | | 097 | *LBL E | 21 15 | f - ϵ_{dB} and start |
| 044 | e ^x | 33 | a | 098 | Pi | 16-24 | |
| 045 | ST02 | 35 02 | | 099 | 2 | 02 | |
| 046 | ENT1 | -21 | | 100 | x | -35 | |
| 047 | 1/X | 52 | | 101 | x | -35 | |
| 048 | - | -45 | | 102 | F3? | 16 23 03 | |
| 049 | 2 | 02 | | 103 | ST03 | 35 03 | w - ϵ_{dB} |
| 050 | \div | -24 | | 104 | F2? | 16 23 02 | |
| 051 | ST00 | 35 13 | $\sinh a$ | 105 | P2S | 16-51 | |
| 052 | RCL2 | 36 02 | | 106 | SPC | 16-11 | |
| 053 | ENT1 | -21 | | 107 | 1 | 01 | |
| 054 | 1/X | 52 | | 108 | ST00 | 35 00 | initialize $2k-1 = 1$ |
| 055 | + | -55 | | | | | |

| REGISTERS | | | | | | | | | |
|-----------|-----------------|--------------|-------------------|----------|--------------|-----|-------|------------|------|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| $2k-1$ | $2Q$ | a or w_n | 1 or w_{-3dB} | | $1/\epsilon$ | R | w_k | σ_k | used |
| S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| A | B | C | D | E | F | G | H | I | |
| n | ϵ_{dB} | $\sinh a$ | $\cosh a$ | $\pi/2n$ | | | | | |

97

[illegible]

97 Program Listing I

| STEP | KEY ENTRY | KEY CODE | COMMENTS | STEP | KEY ENTRY | KEY CODE | COMMENTS |
|------|-----------|----------|----------|------|-----------|----------|----------|
| 001 | *LBLA | 21 11 | START | 056 | ST06 | 35 06 | "p" |
| 002 | F2? | 16 23 02 | | 057 | 1 | 01 | |
| 003 | P2S | 16-51 | | 058 | 2 | 02 | |
| 004 | RCL7 | 36 07 | | 059 | RCL2 | 36 02 | |
| 005 | RCL8 | 36 08 | | 060 | X² | 53 | |
| 006 | P2S | 16-51 | | 061 | x | -35 | |
| 007 | SF2 | 16 21 02 | | 062 | RCL5 | 36 05 | |
| 008 | ST00 | 35 00 | | 063 | ÷ | -24 | |
| 009 | X² | 53 | | 064 | ST08 | 35 08 | "r" |
| 010 | X2Y | -41 | | 065 | CHS | -22 | |
| 011 | X² | 53 | | 066 | RCL3 | 36 03 | |
| 012 | + | -55 | | 067 | x | -35 | |
| 013 | ST01 | 35 01 | | 068 | RCL2 | 36 02 | |
| 014 | 2 | 02 | | 069 | ÷ | -24 | |
| 015 | STX0 | 35-35 00 | | 070 | ST07 | 35 07 | "g" |
| 016 | RCL0 | 36 13 | | 071 | RCL7 | 36 07 | |
| 017 | RCL1 | 36 01 | | 072 | 3 | 03 | |
| 018 | x | -35 | | 073 | x | -35 | |
| 019 | 1/X | 52 | | 074 | RCL6 | 36 06 | |
| 020 | ST02 | 35 02 | 'c' | 075 | X² | 53 | |
| 021 | RCL0 | 36 13 | | 076 | - | -45 | |
| 022 | RCL0 | 36 00 | | 077 | 9 | 09 | |
| 023 | + | -55 | | 078 | ÷ | -24 | |
| 024 | x | -35 | | 079 | ST00 | 35 00 | "a" |
| 025 | ST03 | 35 03 | 'g' | 080 | RCL6 | 36 06 | |
| 026 | RCL0 | 36 13 | | 081 | X² | 53 | |
| 027 | RCL0 | 36 00 | | 082 | 2 | 02 | |
| 028 | x | -35 | | 083 | x | -35 | |
| 029 | RCL1 | 36 01 | | 084 | RCL7 | 36 07 | |
| 030 | + | -55 | | 085 | 9 | 09 | |
| 031 | RCL2 | 36 02 | | 086 | x | -35 | |
| 032 | x | -35 | | 087 | - | -45 | |
| 033 | ST04 | 35 04 | 'A' | 088 | RCL6 | 36 06 | |
| 034 | RCL2 | 36 02 | | 089 | x | -35 | |
| 035 | 4 | 04 | | 090 | 2 | 02 | |
| 036 | x | -35 | | 091 | 7 | 07 | |
| 037 | RCL4 | 36 04 | | 092 | ÷ | -24 | |
| 038 | RCL3 | 36 03 | | 093 | RCL8 | 36 08 | |
| 039 | x | -35 | | 094 | + | -55 | |
| 040 | 2 | 02 | | 095 | 2 | 02 | |
| 041 | x | -35 | | 096 | ÷ | -24 | |
| 042 | - | -45 | | 097 | ST01 | 35 01 | "b" |
| 043 | ST05 | 35 05 | "D" | 098 | X² | 53 | |
| 044 | RCL2 | 36 02 | | 099 | RCL0 | 36 00 | |
| 045 | 4 | 04 | | 100 | 3 | 03 | |
| 046 | x | -35 | | 101 | YX | 31 | |
| 047 | RCL4 | 36 04 | | 102 | + | -55 | |
| 048 | x | -35 | | 103 | 1/X | 52 | |
| 049 | RCL3 | 36 03 | | 104 | ST09 | 35 09 | |
| 050 | X² | 53 | | 105 | RCL1 | 36 01 | |
| 051 | 3 | 03 | | 106 | - | -45 | |
| 052 | x | -35 | | 107 | 3 | 03 | |
| 053 | + | -55 | | 108 | 1/X | 52 | |
| 054 | RCL5 | 36 05 | | 109 | YX | 31 | |
| 055 | ÷ | -24 | | 110 | RCL1 | 36 01 | |

REGISTERS

| REGISTERS | | | | | | | | | | |
|-------------|--------|--------|--------|-----------|---------------|--------|---------|--------------|----------|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 w_k | 8 σ_k | 9 | |
| S0 a, C_1 | S1 b | S2 C | S3 B | S4 A | S5 $D=4C-2AB$ | S6 P | S7 g | S8 r | S9 C_2 | |
| A | | B | | C $Sinha$ | | D | | E | | I |

97 Program Listing II

99

STEP KEY ENTRY KEY CODE

COMMENTS

STEP

KEY ENTRY

KEY CODE

COMMENTS

| | | |
|-----|-------|----------|
| 111 | RCL9 | 36 09 |
| 112 | + | -55 |
| 113 | CH5 | -22 |
| 114 | 3 | 03 |
| 115 | 1/X | 52 |
| 116 | Y* | 31 |
| 117 | + | -55 |
| 118 | RCL6 | 36 06 |
| 119 | 3 | 03 |
| 120 | = | -24 |
| 121 | - | -45 |
| 122 | ST09 | 35 09 |
| 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 | ST00 | 35 00 |
| 136 | RCL9 | 36 09 |
| 137 | x | -35 |
| 138 | 1/X | 52 |
| 139 | RCL2 | 36 02 |
| 140 | x | -35 |
| 141 | RCL9 | 36 09 |
| 142 | RCL0 | 36 00 |
| 143 | P2S | 16-51 |
| 144 | CF2 | 16 22 02 |
| 145 | GSB1 | 23 01 |
| 146 | GSB1 | 23 01 |
| 147 | GSB1 | 23 01 |
| 148 | GT02 | 22 02 |
| 149 | *LBL1 | 21 01 |
| 150 | RCL3 | 36 03 |
| 151 | = | -24 |
| 152 | RCL6 | 36 06 |
| 153 | = | -24 |
| 154 | PRTX | -14 |
| 155 | R4 | -31 |
| 156 | RTN | 24 |
| 157 | *LBL2 | 21 02 |
| 158 | SPC | 16-11 |
| 159 | SPC | 16-11 |
| 160 | RTN | 24 |

C₂

C₁

C₃

C₂

C₁

Impedance and
frequency denormalization
subroutine

170

180

190

200

210

220

LABELS

FLAGS

SET STATUS

| DATA | | | | | | SET STATUS | | | | | | |
|-------|------------|---|---|---|------------|------------|--------------------------|-------------------------------------|------|-------------------------------------|-----|-------------------------------------|
| A | B | C | D | E | 0 | FLAGS | | TRIG | | DISP | | |
| START | | | | | | ON OFF | | | | | | |
| a | b | c | d | e | 1 | 0 | <input type="checkbox"/> | <input type="checkbox"/> | DEG | <input type="checkbox"/> | FIX | <input type="checkbox"/> |
| 0 | 1 output | 2 | 3 | 4 | 2 P23 odd | 1 | <input type="checkbox"/> | <input type="checkbox"/> | GRAD | <input type="checkbox"/> | SCI | <input type="checkbox"/> |
| | subroutine | | | | # of times | 2 | <input type="checkbox"/> | <input checked="" type="checkbox"/> | RAD | <input checked="" type="checkbox"/> | ENG | <input checked="" type="checkbox"/> |
| 5 | 6 | 7 | 8 | 9 | 3 | 3 | <input type="checkbox"/> | <input type="checkbox"/> | | | n | 5 |

NOTES

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Home Management
Small Business
Antennas
Butterworth and Chebyshev Filters
Thermal and Transport Sciences
EE (Lab)
Industrial Engineering
Aeronautical Engineering
Control Systems
Beams and Columns
High-Level Math
Test Statistics
Geometry
Reliability/QA

Medical Practitioner
Anesthesia
Cardiac
Pulmonary
Chemistry
Optics
Physics
Earth Sciences
Energy Conservation
Space Science
Biology
Games
Games of Chance
Aircraft Operation
Aviation
Calendars
Photo Dark Room
COGO-Surveying
Astrology
Forestry

BUTTERWORTH & CHEBYSHEV FILTERS

These programs do almost everything for a filter designer but build the filter.

BUTTERWORTH ACTIVE FILTER DESIGN, LOWPASS
BUTTERWORTH AND CHEBYSHEV FILTER RESPONSE
BUTTERWORTH AND CHEBYSHEV FILTER GROUP DELAY
BUTTERWORTH AND CHEBYSHEV FILTER ORDER CALCULATION
BUTTERWORTH AND CHEBYSHEV LOWPASS NORMALIZED
COEFFICIENTS
NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION
FOR TYPES 1, 2, 6 AND 7
NORMALIZED LOWPASS TO BANDPASS FILTER TRANSFORMATION
FOR TYPES 8, 9, 10 and 11
NORMALIZED LOWPASS TO BANDSTOP, LOWPASS, OR HIGHPASS
Y-DELTA TRANSFORM FOR L, R, OR C
CHEBYSHEV ACTIVE LOWPASS FILTER DESIGN AND POLE
LOCATIONS



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