

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, w_c . The transformation equation becomes:

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

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)

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

$$5 \text{ pF} \leq C \leq 1 \text{ uF}$$

Practical (P)

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

$$2 \text{ pF} \leq C \leq 10 \text{ uF}$$

Marginally practical (M)

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

$$0.5 \text{ pF} \leq C \leq 500 \text{ uF}$$

Impractical (I)

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

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

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

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

$$C > 500 \text{ uF}$$

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

Frequency,

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

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

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

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

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

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

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

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

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)

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

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

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

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

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 $\lambda = 12 \text{ kHz} / 1 \text{ kHz} = 12$ 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.

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

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.

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

$$n = 4$$

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

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

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

$n = 4.000000$ GSBA
Butterworth \rightarrow GSBo

a_1 0.765367 ***
 a_2 1.847759 ***
 a_3 1.847759 ***
 a_4 0.765367 ***

load this program

Bandwidth 1163.301 GSBB
Resistance 1000. GSBC
Lowpass form 1 \rightarrow GSBo

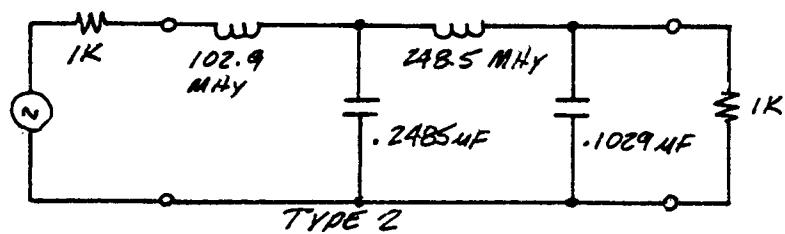
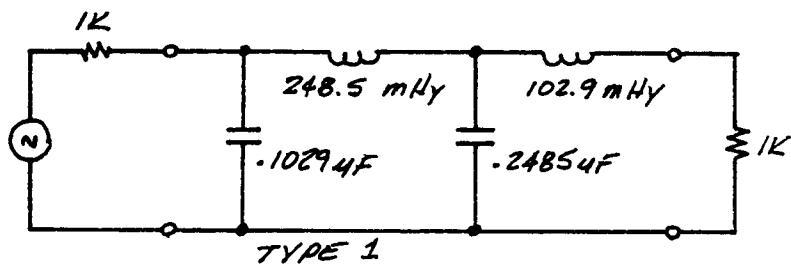
31.

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

Lowpass form 2 \rightarrow GSBB

32.

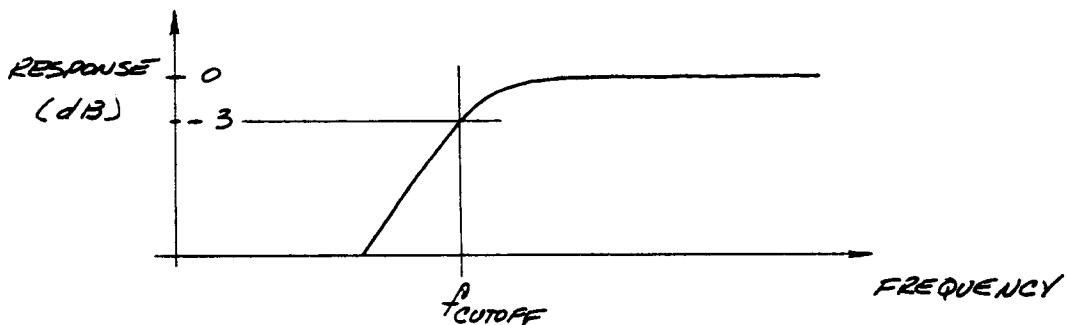
L1 102.9-03 ***
C2 248.5-05 ***
L3 248.5-03 ***
C4 102.9-09 ***



Program Description

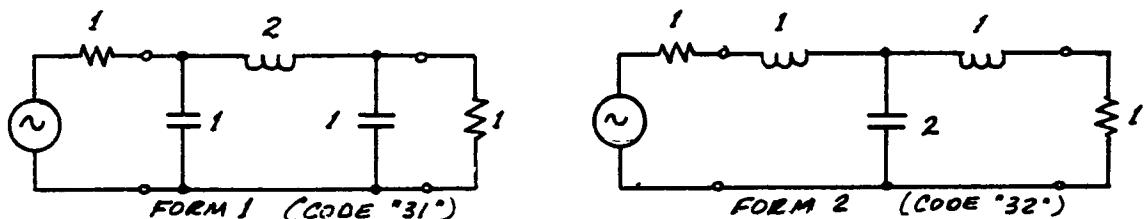
HIGHPASS FILTERS

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.

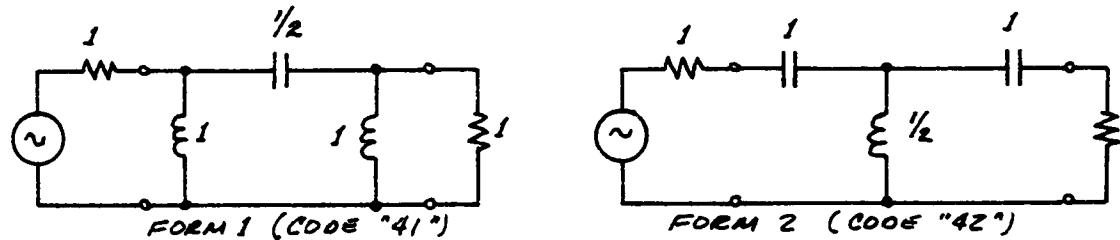


Conceptually the transformation is accomplished by replacing each capacitor with an inductor, and vice versa in the lowpass structure. The normalized highpass component values are the reciprocals of the normalized lowpass values.

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 Ap=1 dB, As=60dB, and $\lambda=54 \text{ mHz}/28\text{mHz} = 1.93$ 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 CONSTANTS PROGRAM

REV IN $A = 7.000000$ GSBA

REV IN $G_B = 1.000000$ GSBB

$\omega_{-3dB} = 1.017205$ ***

$G_1 = 2.166557$ ***

$G_2 = 1.111509$ ***

$G_3 = 3.053642$ ***

$G_4 = 1.173521$ ***

$G_5 = 3.053642$ ***

$G_6 = 1.111509$ ***

$G_7 = 2.166557$ ***

LOAD THIS PROGRAM

BANDWIDTH = 54.06 GSBB

$R = 300$ GSBB

CALCULATE HIGHPASS "1" GSBB

HIGHPASS "1" CODE 41.

$L_1 = 408.1-09$ ***

$C_2 = 8.839-12$ ***

$L_3 = 285.8-09$ ***

$C_4 = 6.372-12$ ***

$L_5 = 285.8-09$ ***

$C_6 = 8.839-12$ ***

$L_7 = 408.1-09$ ***

HIGHPASS "2" GSBB

CODE 42.

$C_1 = 4.535-12$ ***

$L_2 = 795.5-09$ ***

$C_3 = 3.176-12$ ***

$L_4 = 753.5-09$ ***

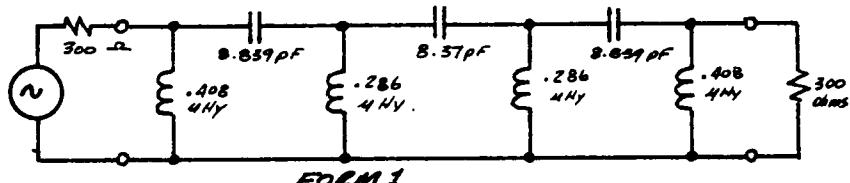
$C_5 = 3.176-12$ ***

$L_6 = 795.5-09$ ***

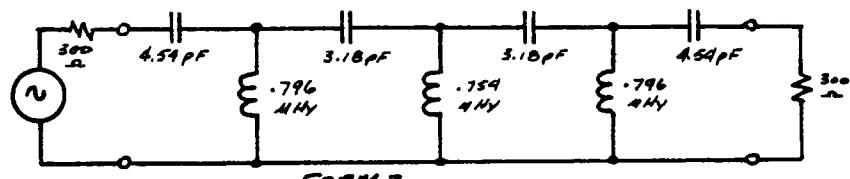
$C_7 = 4.535-12$ ***

SCHEMATICALLY, THE FILTERS ARE

1) UNBALANCED 300 OHM FILTERS:

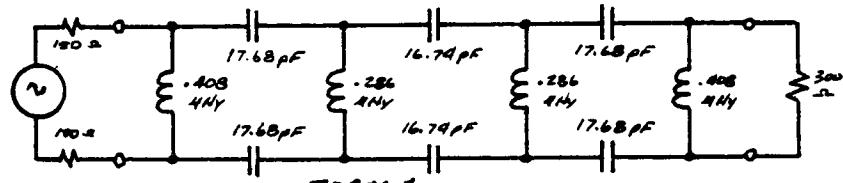


FORM 1

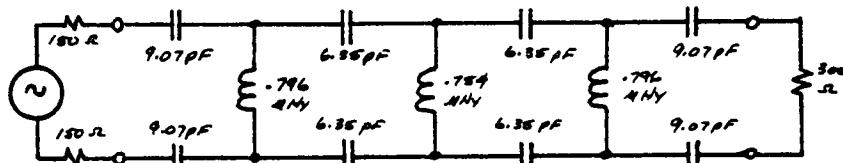


FORM 2

2) EQUIVALENT BALANCED FILTER FORMS



FORM 1



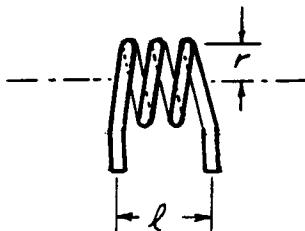
FORM 2

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.



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

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 Gallander's equation:

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

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:

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

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.

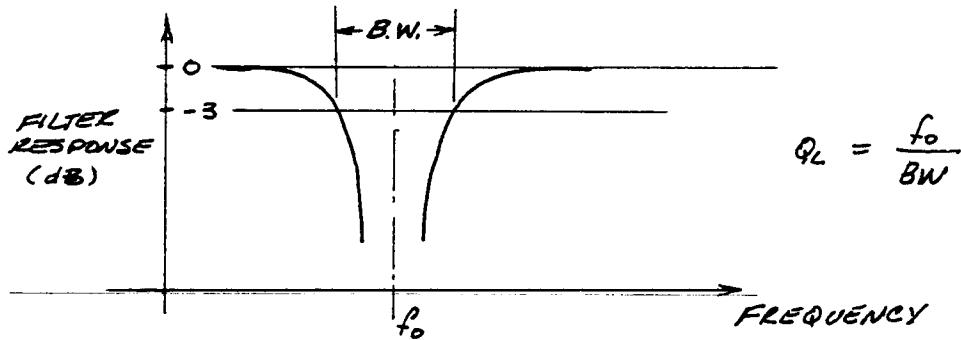
Program Description I

BANDSTOP TRANSFORMATION

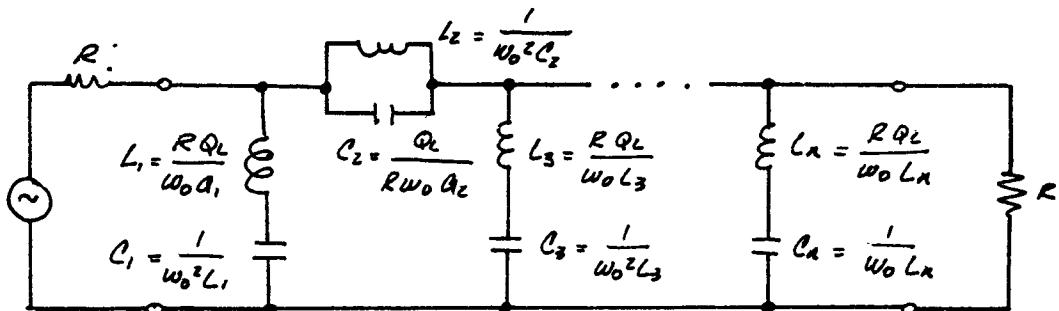
The bandstop filter transmits all frequencies except those lying within a given band of frequencies called the stopband. A subclass of this family of filters are sometimes called notch filters. A typical use of such a filter would be to remove interference, or unwanted signals from within a wanted spectrum.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

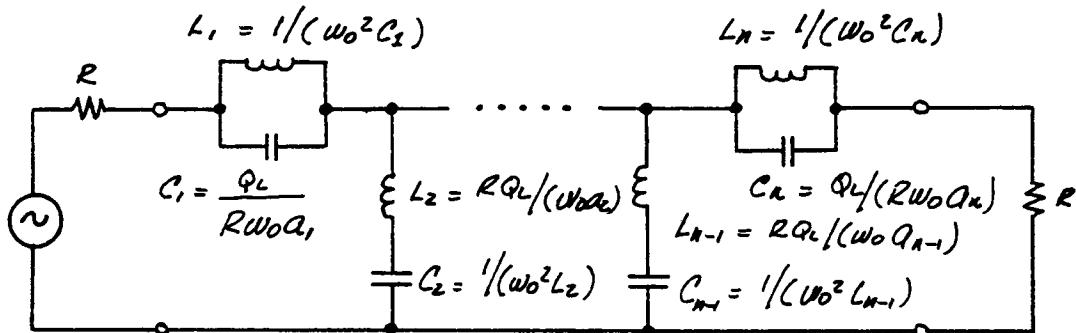


FORM 1 (odd order shown)
(heading "21")

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 $\lambda = 6/4.5 = 1.333\dots$ 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.

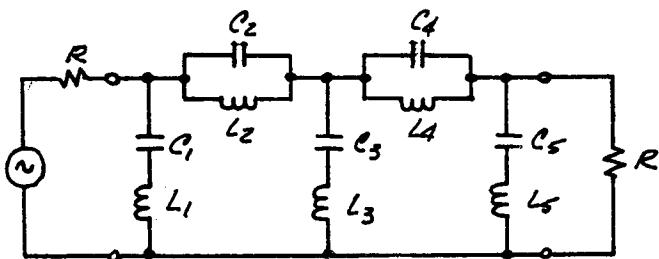
The HP-97 printout is shown on the next page for the above operations, and the two forms of the bandstop filter are shown schematically.

Program Description

LOWPASS NORM. COEF. PROGRAM

INPUT $\{n = 5.000000\}$ GSBA
 $G_{AB} = 1.000000$ GSBE
 $w_{-3dB} = 1.033815$ ***

$G_1 = 2.134882$ ***
 $G_2 = 1.091187$ ***
 $G_3 = 3.006523$ ***
 $G_4 = 1.091187$ ***
 $G_5 = 2.134882$ ***



FORM 1

LOAD BANDSTOP TRANSFORMATION PROGRAM (THIS PROGRAM)

center freq 63.406 GSBA
 Bandwidth 6.406 GSBE
 Termination Resis. 75. GSBC
 Bandstop form 1 GSBD

Bandstop₁ code "21."

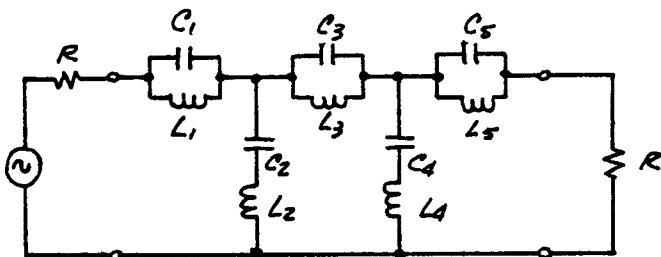
$G_1 = 6.845-12$ ***
 $L_1 = 931.9-09$ ***

$C_2 = 324.1-12$ ***
 $L_2 = 19.69-09$ ***

$C_3 = 9.627-12$ ***
 $L_3 = 662.9-09$ ***

$C_4 = 324.1-12$ ***
 $L_4 = 19.69-09$ ***

$C_5 = 6.849-12$ ***
 $L_5 = 931.9-09$ ***



FORM 2

Bandstop form 2 GSBE

Bandstop₂ code "22."

$C_1 = 165.7-12$ ***
 $L_1 = 38.52-09$ ***

$C_2 = 3.500-12$ ***
 $L_2 = 1.823-06$ ***

$C_3 = 117.9-12$ ***
 $L_3 = 54.15-09$ ***

$C_4 = 3.500-12$ ***
 $L_4 = 1.823-06$ ***

$C_5 = 165.7-12$ ***
 $L_5 = 38.52-09$ ***

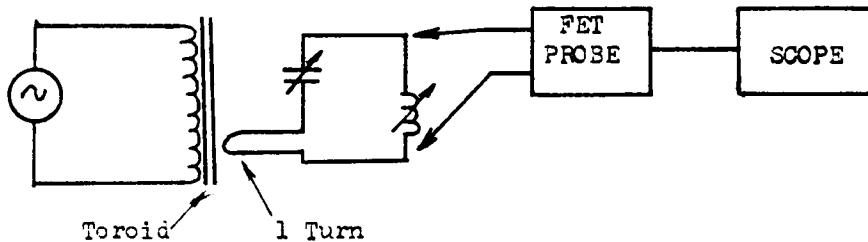
In this particular example, form 2 is more physically realizable than is form 1. In form 1, $L_2 = 19.7$ nH which parallel resonates with $C_2 = 324$ pF. The measured self inductance of a 330 pF silvered mica capacitor is 7.0 nH (105 mHz self resonant frequency). About half of the required resonating inductance is already within the capacitor, which would hinder the coupling into such a tank circuit. The remaining 12.7 nH is the inductance of a .6 inch piece of straight #16 wire!

By contrast, L_1 in form 2 is 38.5 nH, and is resonated by a 165.7 pF capacitor. The measured self inductance of a 160 pF silvered mica capacitor with its leads bent tightly against the case is 5.5 nH (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

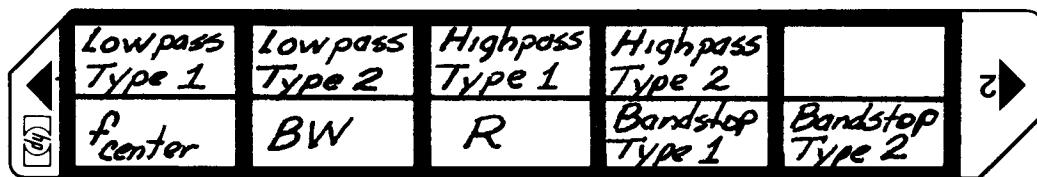
TUNING THE FILTER

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 (certainly 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 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



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

User Instructions

CONTINUED FROM PREVIOUS PAGE

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 \vdots C_n L_n
e)	FOR TYPE 2 FILTER			C_1 L_1 C_2 L_2 \vdots C_n L_n

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	enter center freq.	047	*LBL1	21 01	Bandstop loop
002	F1	16-24	multiply by 2π	048	GSB9	23 09	increment k
003	2	02		049	X \leq Y?	16-35	test for loop exit
004	X	-35		050	RTN	24	
005	X	-35		051	RCL1	36 45	
006	ST00	35 00	store $2\pi f_c$	052	RCL4	36 04	ak
007	RTN	24		053	CF0	16 22 00	
008	*LBL5	21 12	enter bandwidth	054	F1?	16 23 01	test for printorder
009	F1	16-24	multiply by 2π	055	GT06	22 06	
010	X	-35		056	CLX	-51	
011	2	02		057	RCL5	36 05	
012	X	-35		058	SF0	16 21 00	
013	ST01	35 01	store $2\pi BW$	059	*LBL6	21 06	
014	RTN	24		060	GSB8	23 08	calc & print elts.
015	*LBL0	21 13	enter resistance	061	GSB9	23 09	increment k
016	ST02	35 02	store resistance	062	X \leq Y?	16-35	test for loop exit
017	RTN	24		063	RTN	24	
018	*LBLD	21 14	Bandstop Type 1	064	RCL1	36 45	
019	SPC	16-11	print heading	065	RCL5	36 05	
020	2	02	"21"	066	SF0	16 21 00	
021	1	01		067	F1?	16 23 01	test for printorder
022	PRTX	-14		068	GT06	22 06	
023	SPC	16-11		069	CLX	-51	
024	CF1	16 22 01	establish print	070	RCL4	36 04	
025	GT00	22 00	order.	071	CF0	16 22 00	
026	*LBL6	21 15	Bandstop type 2	072	*LBL6	21 06	
027	SPC	16-11	print heading	073	GSB8	23 08	calc & print elts.
028	2	02	"22"	074	GT01	22 01	
029	2	02		075	*LBL8	21 06	calculate and print
030	PRTX	-14		076	X	-35	subroutine for
031	SPC	16-11		077	ST08	35 08	bandstop filters
032	SF1	16 21 01	estab print order	078	F0?	16 23 00	
033	*LBL0	21 00	calc bandstop coeffs	079	PRTX	-14	
034	RCL2	36 02	R	080	RCL0	36 00	
035	RCL1	36 01	$2\pi BW$	081	X ²	53	
036	X	-35		082	X	-35	
037	RCL0	36 00	w_o	083	1/X	52	
038	X ²	53		084	PRTX	-14	
039	=	-24		085	F0?	16 23 00	
040	ST04	35 04		086	GT06	22 06	
041	RCL2	36 02		087	RCL8	36 08	
042	X ²	53		088	PRTX	-14	
043	=	-24		089	*LBL6	21 06	
044	ST05	35 05		090	SPC	16-11	
045	0	00	initialize k	091	RTN	24	
046	ST07	35 07		092	*LBL0	21 16 11	lowpass type 1
				093	SPC	16-11	print heading
				094	3	03	"31"
				095	1	01	
				096	PRTX	-14	
050				097	SPC	16-11	
				098	CF0	16 22 00	
				099	GSB7	23 07	calculate consts
				100	GT02	22 02	goto output rout.

REGISTERS

0	$2\pi f_c$	1	$2\pi BW$	2	R	3		4	<u>used</u>	5	<u>used</u>	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		F		G		H	$index$	I			

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	$2\pi BW$
104	2	02	"32"	158	\div	-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	\div	-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	STx5	35-35 05		166	RTN	24	
113	GT02	22 02	goto output routine	167	*LBL9	21 09	increment k and test loop exit
114	*LBL0	21 16 14	Highpass Type 2	168	1	01	
115	SPC	16-11	print heading	169	ST \div 7	35-55 07	
116	4	04		170	RCL7	36 07	
117	2	02	"42"	171	9	09	
118	PRTX	-14		172	\div	-55	
119	SPC	16-11		173	ST01	35 46	
120	SFG	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	*LBL0	21 16 13	Highpass Type 1	177	\div	-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	SFG	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	STx5	35-35 05					
135	*LBL2	21 02	lopass/hipass out.				
136	GSB9	23 05	increment k				
137	X \leq 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	210			
143	X	-35					
144	PRTX	-14	print element				
145	GSB9	23 05	increment k				
146	X \leq 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	220			
152	X	-35					
153	PRTX	-14	print element				
154	GT02	22 02	loop				

LABELS

LABELS					FLAGS	SET STATUS		
A Store	B Store	C Store	D Bandstop	E Bandstop	0 used	FLAGS	TRIG	DISP
$W_0 = 2\pi f_0 \rightarrow R_0$	$2\pi f_0 \rightarrow R_1$	$R_2 \rightarrow R_2$	Type 1	Type 2	0 used	ON OFF	DEG	FIX
a Lowpass	b Lowpass	c Highpass	d Highpass	e Type 2	1 used	0 <input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Type 1	Type 2	Type 1	Type 2			1 <input type="checkbox"/>	<input type="checkbox"/>	SCI
0 Bandstop	1 Bandstop	2 pass/Hipass	3	4	2	2 <input type="checkbox"/>	<input type="checkbox"/>	ENG
Coef calc	Loop dest.	Loop return				3 <input type="checkbox"/>	<input checked="" type="checkbox"/>	n 3
5	6 Local loop	7 High pass	8 Bandstop	9 increment k	3			
	destination	Coefficients	output routine	and test exit				

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

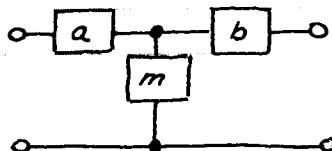
State CALIF

Zip Code 93017

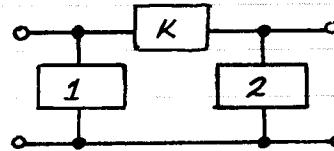
Program Description, Equations, Variables This program performs the Y- Δ transform for trios of resistors, inductors, or capacitors. These transformations find use wherever awkward or physically impractical element values result from electrical network design. The resistive transform is oftentimes used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

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

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

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

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

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

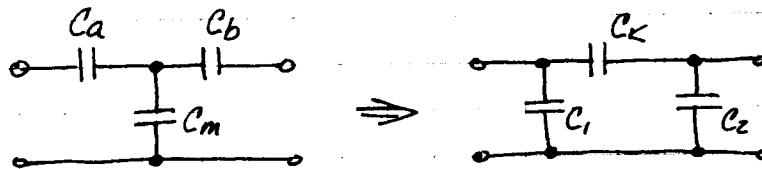
This program has been verified only with respect to the numerical example given in *Program Description II*. User accepts and uses this program material AT HIS OWN RISK, in reliance solely upon his own inspection of the program material and without reliance upon any representation or description concerning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

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Program Description II

Sketch(es)

Convert the following Capacitor networks.



Sample Problem(s) For $C_a = 1\text{uF}$, $C_b = 3.4\text{uF}$, and $C_m = 2\text{uF}$ 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.

$$\sum C \text{ before } xtm = 6\text{uF}$$

Solution(s) Enter data into program $1E-6$, $2E-6$, $3E-6$, elements are capacitors . To list input elements . To perform $Y \rightarrow \Delta$ transform *. To list transformed elements . The transformed element values are: $C_1 = 0.333\text{uF}$, $C_k = 0.5\text{uF}$, $C_2 = 1.00\text{uF}$, and $\sum C' \text{S} = 1.833\text{uF}$. The total capacity has been reduced by 69.4%!

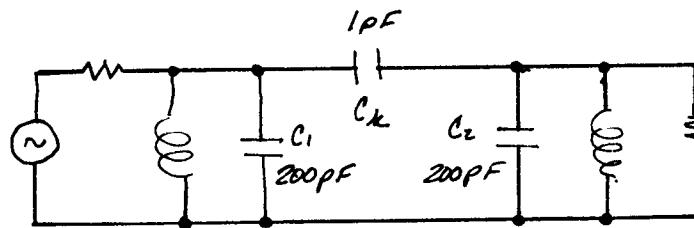
Reference(s) Wernberg, Louis; Network analysis and Synthesis; Wiley

* calls both before and after transformation. lists the currently stored element values.

Program Description I

A MORE PRACTICAL TRANSFORMATION EXAMPLE:

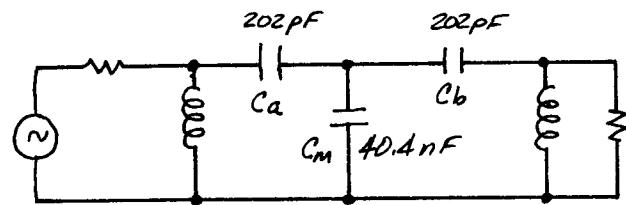
A TOP COUPLED PARALLEL RESONANT BANDPASS FILTER HAS BEEN DESIGNED USING THE TYPE 7 FILTER PROGRAM. THE ELEMENT VALUES ARE SHOWN:



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 NYE CONFIGURATION TO OBTAIN A BETTER SELECTION OF ELEMENT VALUES.

ENG
 DSP3
 200.-12 GSBA
 GSBC
 1.-12 GSBB
 GSBA
 GSBE
 } DATA ENTRY
 200.0-12 *** C1
 1.000-12 *** Ck
 200.0-12 *** C2
 401.0-12 *** ZC

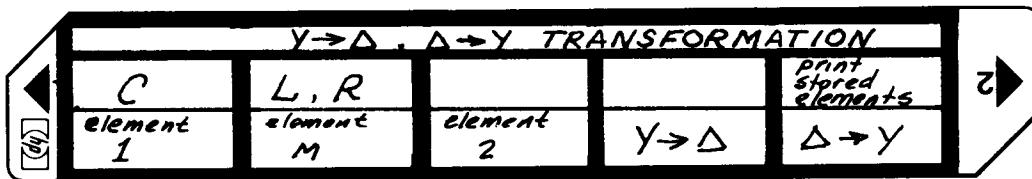
 $\Delta \rightarrow Y$ xfm
 202.0-12 *** Ca
 40.40-09 *** Cm
 202.0-12 *** Cb
 40.60-09 *** ZC's



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			
2	SELECT ELEMENT TYPE a) IF CAPACITORS b) IF INDUCTORS OR RESISTORS		f A f B	
3	LOAD ELEMENTS Y or Δ a) LOAD ELEMENT a or 1 b) LOAD ELEMENT m or k c) LOAD ELEMENT b or 2		A B C	
4	OBTAIN TRANSFORMED ELEMENTS a) Y->Δ TRANSFORMATION		D	ELEMENT a " m " b $\Sigma a, m, b$
				ELEMENT 1 " k " 2 $\Sigma 1, k, 2$
	b) Δ->Y TRANSFORMATION		E	ELEMENT 1 " k " 2 $\Sigma 1, k, 2$
				ELEMENT a " m " b $\Sigma a, m, b$
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	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
002	STOA	35 11		030	GSBe	23 16 15	
003	RTN	24		031	F07	16 23 00	
004	*LBLB	21 12	ENTER ELEMENT k or m	032	GT00	22 00	
005	STOB	35 12		033	*LBL1	21 01	A → Y ROUTING FOR RESISTORS AND INDUCTORS
006	RTN	24		034	RCIA	36 11	
007	*LBLC	21 13	ENTER ELEMENT 2 or b	035	RCIB	36 12	
008	STOC	35 13		036	+	-55	
009	RTN	24		037	RCIC	36 13	
010	*LBLa	21 16 11	CLEAR FLAG 0 TO INDICATE CAPACITORS	038	+	-55	
011	CFO	16 22 00		039	STOD	35 14	
012	RTN	24		040	RCIA	36 11	
013	*LBLb	21 16 12	SET FLAG 0 TO INDICATE RESISTORS OR INDUCTORS	041	RCIB	36 12	
014	SFO	16 21 00		042	X	-35	
015	RTN	24		043	RCIC	36 14	
016	*LBLc	21 16 15	PRINT STORED ELEMENTS AND SUM OF STORED ELEMENTS	044	÷	-24	
017	SFC	16-11		045	STOE	35 15	
018	RCIA	36 11		046	RCIA	36 11	
019	PRTX	-14		047	RCIC	36 13	
020	RCIB	36 12		048	X	-35	
021	PRTX	-14		049	RCIC	36 14	
022	+	-55		050	÷	-24	
023	RCIC	36 13		051	RCLE	36 15	
024	PRTX	-14		052	STOA	35 11	
025	+	-55		053	R↓	-31	
026	PRTX	-14		054	STOE	35 15	
027	SPC	16-11		055	RCIB	36 12	
028	RTN	24		056	RCIC	36 13	
				057	X	-35	
				058	RCIC	36 14	
				059	÷	-24	
				060	STOC	35 13	
				061	RCLE	36 15	
				062	STOB	35 12	
				063	GT0e	22 16 15	
REGISTERS							
0	1	2	3	4	5	6	7
S0	S1	S2	S3	S4	S5	S6	S7
A ELEMENT 1 or a	B ELEMENT k or m	C ELEMENT 2 or b	D $\Sigma X \text{ or } \Sigma XX$ $X = L, R \text{ or } C$	E used	I		

Program Listing II

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STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
064	*LBL0	31 15					
065	GSE _e	23 16 15	$\Delta \rightarrow Y$ TRANSFORM				
066	F07	16 23 00	FOR CAPACITORS				
067	GT01	22 01	OR				
068	*LBL0	21 00					
069	RCLA	36 11	$Y \rightarrow \Delta$ TRANSFORM				
070	RCLB	36 12	FOR RESISTORS				
071	X	-35	AND INDUCTORS				
072	RCLB	36 12					
073	RCLC	36 13					
074	X	-35					
075	+	-55					
076	RCLH	36 11					
077	RCLC	36 13					
078	X	-35					
079	+	-55					
080	ST0D	35 14					
081	RCLC	36 13					
082	÷	-24					
083	ST0E	35 15					
084	RCLD	36 14					
085	RCLB	36 12					
086	÷	-24					
087	ST0B	35 12					
088	RCLD	36 14					
089	RCLH	36 11					
090	÷	-24					
091	ST0C	35 13					
092	RCLE	36 15					
093	ST0A	35 11					
094	GT0e	22 16 15					

LABELS					FLAGS		SET STATUS		
A ELEMENT 1. OR ENTRY	B ELEMENT 2. OR M ENTRY	C ELEMENT 2. OR b ENTRY	D Y → Δ x1m	E Δ → Y x1m	0 0 = CAP "1" = LORR	FLAGS	TRIG	DISP	
a SET CAPACITOR	b SET INDUCTOR OR RESISTOR	c	d	e PRINT ELEMENTS	1	ON OFF	DEG ■	FIX ■	
0 LORR DESTINATION	1 LORR DESTINATION	2	3	4	2	1 □ ■	GRAD □	SCI □	
5	6	7	8	9	3	2 □ ■	RAD □	ENG □	
						3 □ ■	n 5		

Program Description I

Program Title CHEBYCHEV ACTIVE LOWPASS FILTER DESIGN AND POLE LOCATIONS

Contributor's Name Bruce K. Murdock

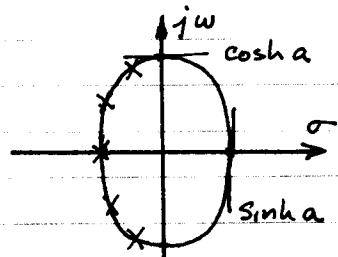
Address 6875 Sabado Tarde Road

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

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



pole locations:

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

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

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

5th order pole locations

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

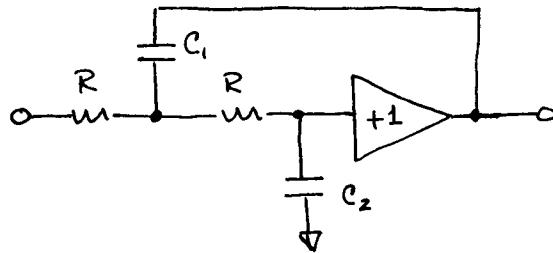
Each pole pair location may be expressed in terms of real and imaginary parts which is the Cartesian coordinate system, or the polar coordinate system may be used, in which case the pole pair location may be expressed by a natural frequency, w_n , and a Q, or quality factor. The relation between these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

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

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

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

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



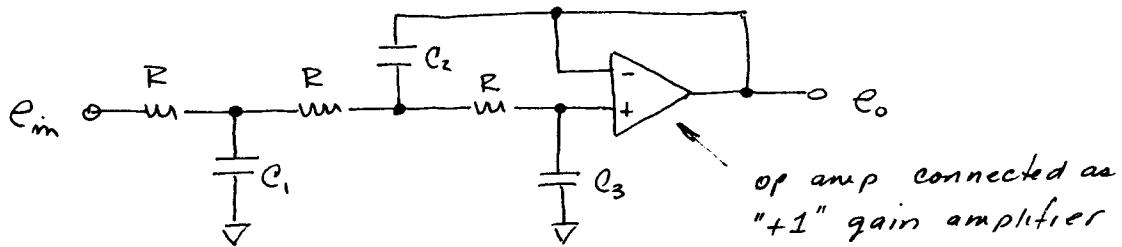
$$C_1 = \frac{2Q}{w_n R} \quad ; \quad C_2 = \frac{C_1}{4Q^2}$$

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



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

$$A = C_1 + 3C_3 = \frac{1}{\omega_n Q} + \frac{1}{\omega_n^2}$$

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

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

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 hand book 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

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

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

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

once C_2 is obtained, the other capacitor values follow

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

and

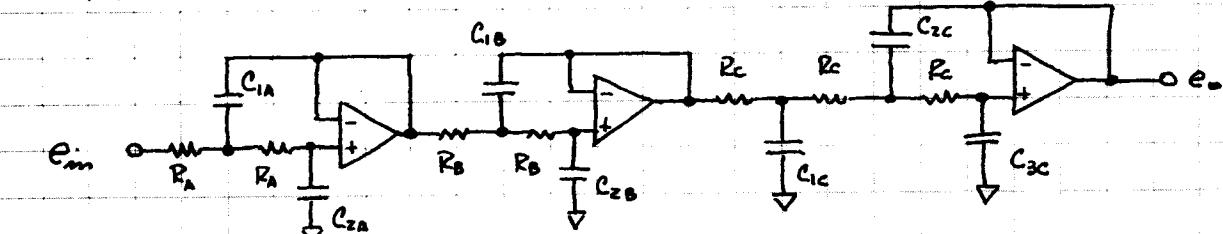
$$C_3 = \frac{C}{C_1 C_2}$$

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 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, for 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 $\omega = 2000/1000 = 2$.

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. 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 *** W_A
 10.8987+00 *** Q
 348.192-09 *** C_{1A}
 732.846-12 *** C_{2A}

second resonator (second order)

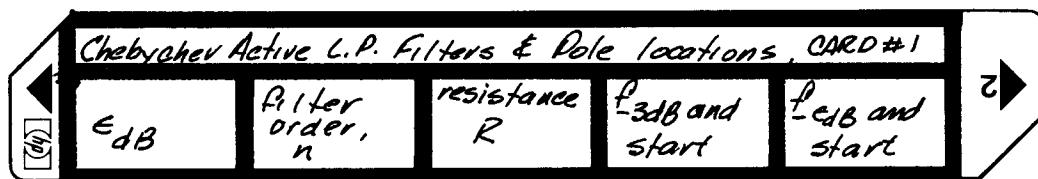
5.07911+03 *** W_A
 3.15586+00 *** Q
 124.268-09 *** C_{1B}
 3.11935-09 *** C_{2B}

third resonator (third order)

3.01626+03 *** W_A
 1.29693+00 *** Q } second order pole pair
 1.29066+03 *** ~~C~~
 84.2120-09 *** C_{1C}
 161.111-09 *** C_{2C}
 6.27702-09 *** C_{3C}

load second card here & press **[A]**

User Instructions



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1.	LOAD PROGRAM			
2	KEY IN PASSBAND RIPPLE IN dB	E_{dB}		
3	KEY IN FILTER ORDER	n		
4	KEY IN DE-NORMALIZATION RESISTANCE	R		
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 - E_{dB} DOWN AT CUTOFF FREQUENCY	f_{CUTOFF}	E	W_{n1} Q_1 C_{11} C_{21}
				W_{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	W_{n1} Q_n C_{1n} C_{2n}
			ODD ORDER	W_{n1} Q_n C_{1n} C_{2n} C_{3n}

User Instructions

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

1

2

START

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL4	21 11		056	2	02	
002	F2?	16 23 02		057	÷	-24	
003	P±S	16-51		058	ST00	35 14	
004	ST06	35 12		059	RTN	24	
005	RTN	24		060	*LBL0	21 13	
006	*LBLB	21 12		061	F2?	16 23 02	
007	F2?	16 23 02		062	P±S	16-51	
008	P±S	16-51		063	ST06	35 06	
009	ST0A	35 11		064	RTN	24	
010	2	02		065	*LBL0	21 14	
011	÷	-24		066	Pi	16-24	
012	ENT↑	-21		067	2	02	
013	INT	16 34		068	X	-35	
014	CF0	16 22 00		069	X	-35	
015	X=Y?	16-33		070	F3?	16 23 03	
016	SF0	16 21 00		071	ST09	35 09	
017	*LBL4	21 04		072	F2?	16 23 02	
018	RCLA	36 11		073	P±S	16-51	
019	2	02		074	RCL5	36 05	
020	X	-35		075	ENT↑	-21	
021	1/X	52		076	X ²	53	
022	Pi	16-24		077	1	01	
023	X	-35		078	-	-45	
024	ST0E	35 15		079	JX	54	
025	RCLB	36 12		080	+	-55	
026	1	01		081	LH	32	
027	0	00		082	RCLA	36 11	
028	÷	-24		083	÷	-24	
029	10 ^x	16 33		084	e ^x	33	
030	1	01		085	ENT↑	-21	
031	-	-45		086	1/X	52	
032	JX	54		087	+	-55	
033	1/X	52		088	2	02	
034	ST05	35 05		089	÷	-24	
035	ENT↑	-21		090	1/X	52	
036	X ²	53		091	RCL9	36 09	
037	1	01		092	X	-35	
038	+	-55		093	ST03	35 03	
039	JX	54		094	1	01	
040	+	-55		095	ST00	35 00	
041	LH	32		096	GT01	22 01	
042	RCLA	36 11		097	*LBL0	21 15	
043	÷	-24		098	Pi	16-24	
044	e ^x	33		099	2	02	
045	ST02	35 02		100	X	-35	
046	ENT↑	-21		101	X	-35	
047	1/X	52		102	F3?	16 23 02	
048	-	-45		103	ST03	35 03	
049	2	02		104	F2?	16 23 02	
050	÷	-24		105	P±S	16-51	
051	ST00	35 13		106	SPC	16-11	
052	RCL2	36 02		107	1	01	
053	ENT↑	-21		108	ST00	35 00	
054	1/X	52					
055	+	-55					

REGISTERS

0	1	2	3	4	5	6	7	8	9
$2k-1$	$2q$	a or w_n	1 or w_{3dB}		$1/e$	R	w_k	σ_k	u_{red}
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	n	B	E_{dB}	C	$\sinh a$	D	$\cosh a$	E	$\pi/2n$

97 Program Listing II

LABELS

A	ENTER E _{DB}	B	ENTER n	C	ENTER R	D	$\frac{1}{3}18$ start	E	f _{edb} start	0	n even	FLAGS	TRIG	DISP				
a	b	c	d	e						1		ON	OFF					
0	1 <i>Wn & Q calc</i>	2 <i>odd order output</i>	3 <i>even order output</i>	4						2 PES used. add # times		DEG	<input type="checkbox"/>	FIX	<input type="checkbox"/>			
5	6	7	8	9						3		1	<input type="checkbox"/>	GRAD	<input type="checkbox"/>	SCI	<input type="checkbox"/>	
												2	<input type="checkbox"/>	<input type="checkbox"/>	RAD	<input checked="" type="checkbox"/>	ENG	<input checked="" type="checkbox"/>
												3	<input type="checkbox"/>	<input type="checkbox"/>			n 5	

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11		056	ST06	35 06	
002	F2?	16 23 02		057	1	01	"P"
003	P±S	16-51		058	2	02	
004	RCL7	36 07		059	RCL2	36 02	
005	RCL8	36 06		060	X ²	53	
006	P±S	16-51		061	X	-35	
007	SF2	16 21 02		062	RCL5	36 05	
008	ST00	35 06		063	÷	-24	
009	X ²	53		064	ST06	35 06	"r"
010	X ² Y	-41		065	CHS	-22	
011	X ²	53		066	RCL3	36 03	
012	+	-55		067	X	-35	
013	ST01	35 01		068	RCL2	36 02	
014	Z	02		069	÷	-24	
015	STX0	35-35 00		070	ST07	35 07	"q"
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	X ²	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	
025	ST03	35 03	"B"	080	RCL6	36 06	"a"
026	RCL0	36 13		081	X ²	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	35 04		092	÷	-24	
038	RCL3	36 03		093	RCL8	36 08	
039	X	-35		094	+	-55	
040	Z	02		095	2	02	
041	X	-35		096	÷	-24	
042	-	-45		097	ST01	35 01	"b"
043	ST05	35 05	"D"	098	X ²	53	
044	RCL2	36 02		099	RCL0	36 00	
045	4	04		100	3	03	
046	X	-35		101	Y ²	31	
047	RCL4	36 04		102	+	-55	
048	X	-35		103	JX	54	
049	RCL3	36 03		104	ST09	35 09	$\sqrt{b^2 + a^2}$
050	X ²	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	Y ²	31	
055	÷	-24		110	RCL1	36 01	

REGISTERS

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

97 Program Listing II

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

NOTES

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