HEWLETT-PACKARD

HP-67/HP-97

Users' Library Solutions

Butterworth and Chebyshev Filters

$30

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(CONT.)

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.

Program Description I

HIGHPASS, BANDPASS, AND BANDSTOP TRANSFORMATIONS IN ANALYTICAL FORM

1) HIGHPASS TRANSFORMATION

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

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

The highpass transformed magnitude response is:

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

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

2) BANDPASS TRANSFORMATION

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

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

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

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

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

3) BANDSTOP TRANSFORMATION

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

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

The Butterworth equation for the lowpass magnitude response transforms thus:

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

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

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

Program Description I

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

Readily Realizable (R)

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

Practical (P)

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

Marginally practical (M)

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

Impractical (I)

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

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

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

Frequency,

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

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

Loaded Q (Q_L), for bandpass and bandstop,

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

Impedance Level (source and load resistances equal)

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

Program Description I

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

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

Courtesy, Don White Consultants Inc.

Program Description I

LOWPASS FILTERS

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

L, scaled = (L, normalized)•(R/(2πBW))

C, scaled = (C, normalized)•(1/(2π(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 λ = 12 kHz/1 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. $As^2-1 = (Ap^2-1)\lambda^{2n}$. This equation may be rearranged to solve for n:

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

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

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

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

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

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

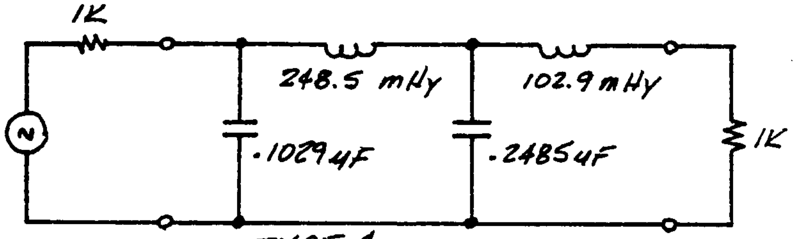
λ = 1.183301 , then

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

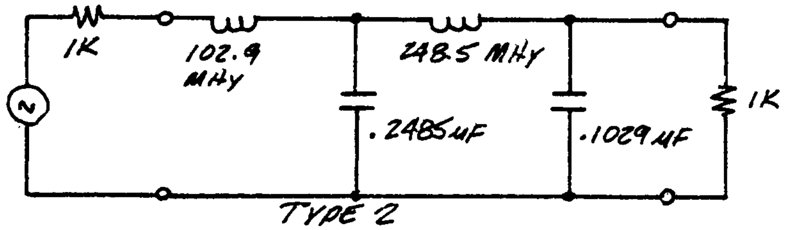
Program Description

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

```
Lowpass normalized program

        n =  4.000000 GSBA
  Butterworth  -->    GSBa

        a1   0.765367  ***
        a2   1.847759  ***
        a3   1.847759  ***
        a4   0.765367  ***
_________________________________
 load this program

  Bandwidth  1163.301 GSBB
  Resistance    1000. GSBC
  Lowpass form 1  --> GSBa

                 31.

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


  Lowpass form 2  --> GSBb

                 32.

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



TYPE 1

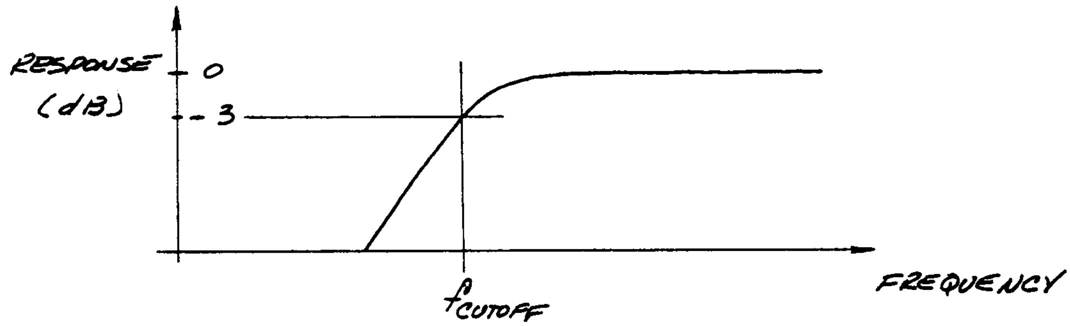


TYPE 2

Program Description

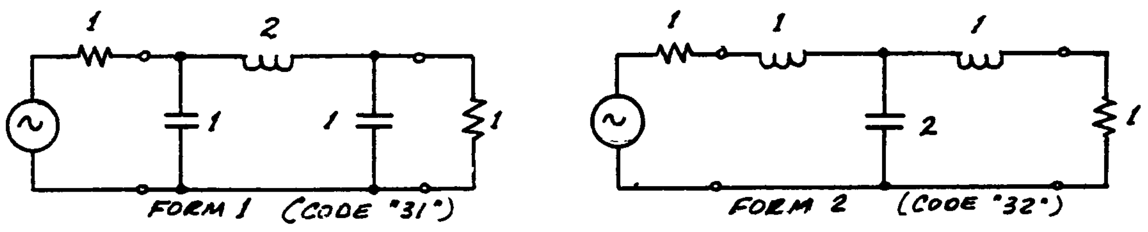
HIGHPASS FILTERS

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

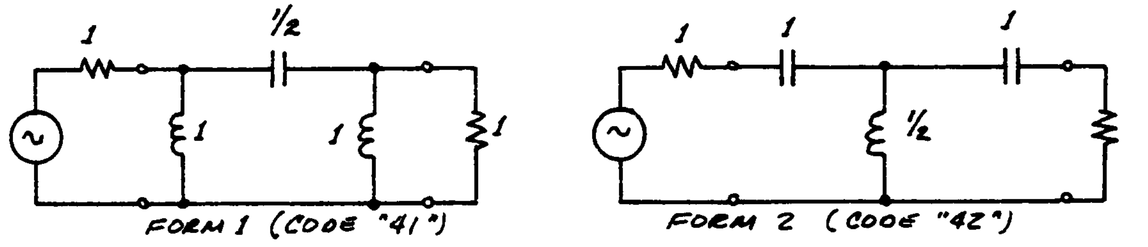


Conceptually the transformation is accomplished by replacing each capacitor with an inductor, and vice versa in the lowpass structure. The normalized highpass component values are the recipricals of the normalized lowpass values.

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



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.

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

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

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

EXAMPLE: A highpass filter is needed in the antenna lead of a tv set to reject the carrier signal from a nearby amateur radio transmitter as this signal is strong enough to cause cross modulation in the tuner of the tv set. The low end of channel 2's spectrum is 54 mHz, and the transmitter is operating at 28 mHz. 1 dB of attenuation and ripple will be allowed across the tv spectrum. At least 60 dB of attenuation is required at 28 mHz. The filter is to be placed in a 300 Ohm balanced line. Because of the allowed ripple, a Chebychev filter may be used. One may use the Chebychev nomograph, or another program of this set to solve for the filter order, n. Using the nomograph and entering $Ap = 1$ dB, $As = 60$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 ½ the desired level, then draw the unbalanced filter plus it's mirror image below the common line. The common line is erased, and shunt elements combined. The other way is to design the filter at the desired impedance level, and then to replace each series element with two series elements having the same total impedance. One of these new series elements is then placed in the common line opposite the mate. This method will be used in this example.

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

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

Program Description

LOAD NORMALIZED LOWPASS PROGRAM

KEY IN n = 7.000000 GSBA
KEY IN G_{dB} = 1.000000 GSBB
ω_{-3dB} = 1.017265 ***

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

LOAD THIS PROGRAM

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

HIGHPASS "1" CODE 41.

L_1 = 408.1-09 ***
C_2 = 8.839-12 ***
L_3 = 285.8-09 ***
C_4 = 6.372-12 ***
L_5 = 285.8-09 ***
C_6 = 8.839-12 ***
L_7 = 408.1-09 ***

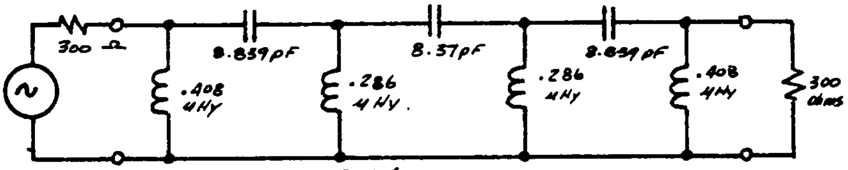
HIGHPASS "2" GSBd

CODE 42.

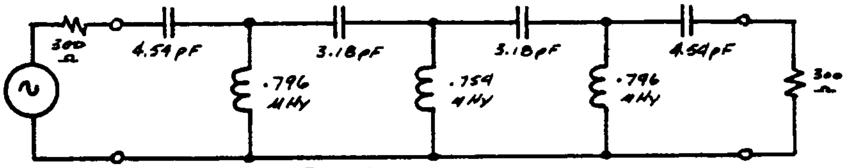
C_1 = 4.535-12 ***
L_2 = 795.5-09 ***
C_3 = 3.176-12 ***
L_4 = 753.5-09 ***
C_5 = 3.176-12 ***
L_6 = 795.5-09 ***
C_7 = 4.535-12 ***

SCHEMATICALLY, THE FILTERS ARE

1) UNBALANCED 300 OHM FILTERS:

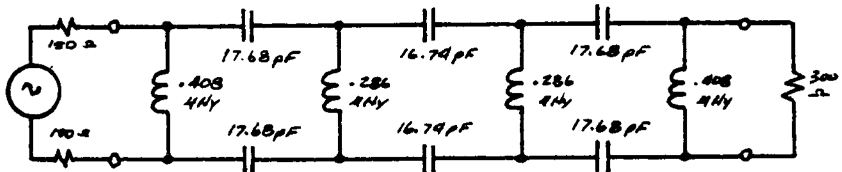


FORM 1

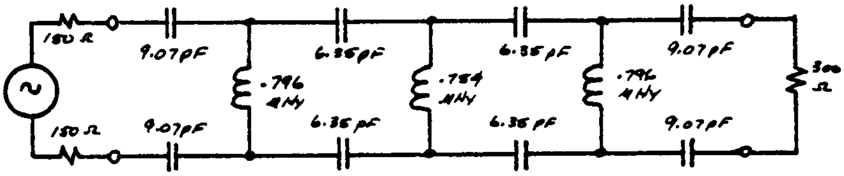


FORM 2

2) EQUIVALENT BALANCED FILTER FORMS



FORM 1

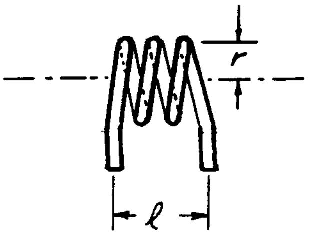


FORM 2

INDUCTOR DESIGN

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

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



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

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

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

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

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

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

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

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

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

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

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

Program Description I

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

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

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

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

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

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

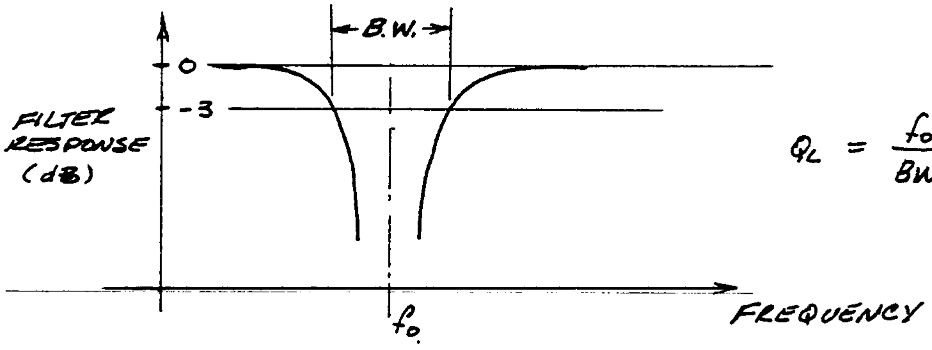
Program Description I

BANDSTOP TRANSFORMATION

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

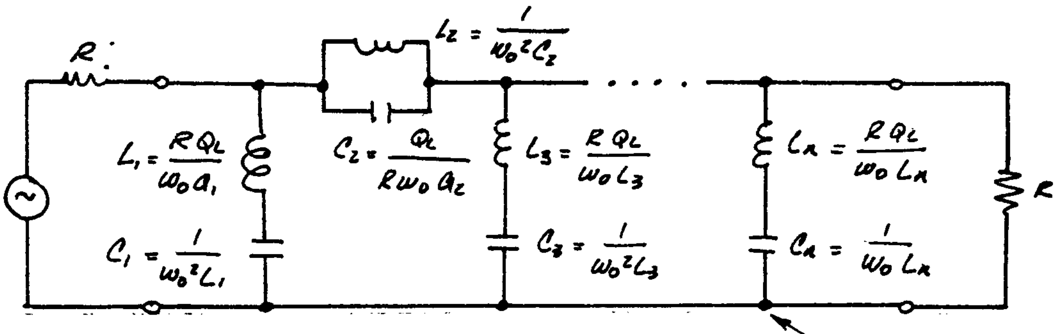
Conceptually the transformation is accomplished by designing a highpass filter whose cutoff frequency equals the bandwidth of the desired bandstop filter. Each shunt inductor in the highpass filter is series resonated with a capacitor at the desired center frequency of the filter. Likewise, each series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

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



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

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

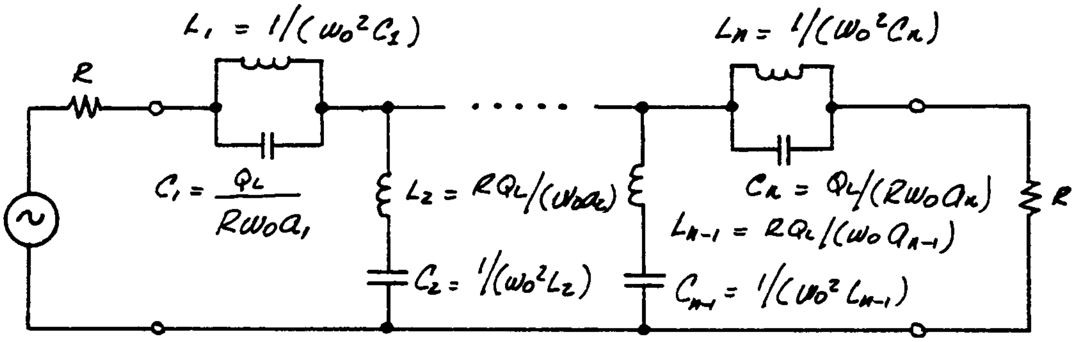


FORM 1 (odd order shown)
(heading "21")

even ordered filter stops here

Program Description I

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



FORM 2 (heading "22")

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

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

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

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

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

Program Description

LOWPASS NORM COEF PROGRAM

input	n =	5.000000	GSBA
	GdB	1.000000	GSBB
ω_{-3dB}	=	1.033615	***
	G_1	2.134882	***
	G_2	1.091107	***
	G_3	3.000923	***
	G_4	1.091107	***
	G_5	2.134882	***

LOAD BANDSTOP TRANSFORMATION PROGRAM (THIS PROGRAM)

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

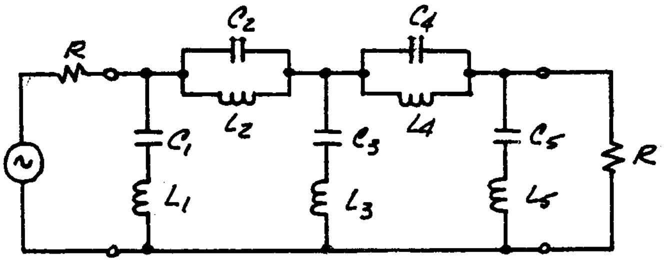
Bandstop$_1$ code "21."

C_1 =	6.849-12	***
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	***

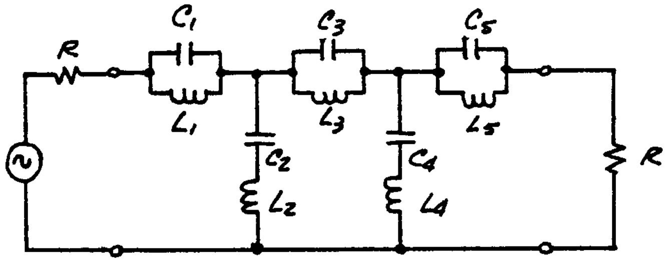
Bandstop form 2 GSBE

Bandstop$_2$ 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	***



FORM 1



FORM 2

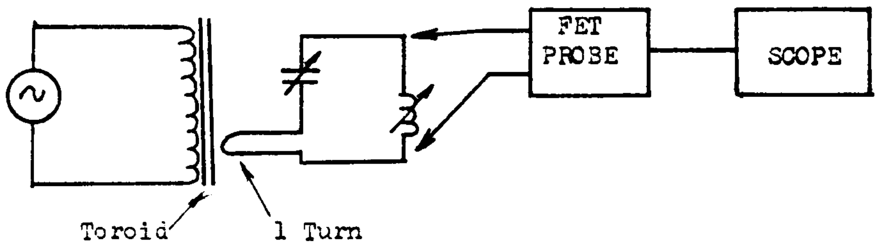
In this particular example, form 2 is more physically realizable than is form 1. In form 1, L2 = 19.7 nHy which parallel resonates with C2 = 324 pF. The measured self inductance of a 330 pF silvered mica capacitor is 7.0 nHy (105 mHz self resonant frequency) About half of the required resonating inductance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

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

Program Description

TUNING THE FILTER

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



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

User Instructions

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

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

User Instructions

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
4	FOR BANDSTOP COMPONENT VALUES			
	a) LOAD CENTER FREQ	fcenter	A	2π fc
	b) LOAD BANDWIDTH	BW	B	2π BW
	c) LOAD RESISTANCE LEVEL	R	C	R
	d) FOR TYPE 1 FILTER		D	C_1
				L_1
				C_2
				L_2
				⋮
				C_n
				L_n
	e) FOR TYPE 2 FILTER			C_1
				L_1
				C_2
				L_2
				⋮
				C_n
				L_n

97 Program Listing I

09408D

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	enter center freq.
002	Pi	16-24	multiply by 2π
003	2	02	
004	×	-35	
005	×	-35	
006	STO0	35 00	store $2\pi f_c$
007	RTN	24	
008	*LBLB	21 12	enter bandwidth
009	Pi	16-24	multiply by 2π
010	×	-35	
011	2	02	
012	×	-35	
013	STO1	35 01	store 2πBW
014	RTN	24	
015	*LBLC	21 13	enter resistance
016	STO2	35 02	store resistance
017	RTN	24	
018	*LBLD	21 14	Bandstop Type 1
019	SPC	16-11	print heading
020	2	02	"21"
021	1	01	
022	PRTX	-14	
023	SPC	16-11	
024	CF1	16 22 01	establish print
025	GTO0	22 00	order.
026	*LBLE	21 15	Bandstop type 2
027	SPC	16-11	print heading
028	2	02	"22"
029	2	02	
030	PRTX	-14	
031	SPC	16-11	
032	SF1	16 21 01	estab print order
033	*LBL0	21 00	calc bandstop coefs
034	RCL2	36 02	R
035	RCL1	36 01	2πBW
036	×	-35	
037	RCL0	36 00	w_o
038	X²	53	
039	÷	-24	
040	STO4	35 04	
041	RCL2	36 02	
042	X²	53	
043	÷	-24	
044	STO5	35 05	
045	0	00	initialize k
046	STO7	35 07	
047	*LBL1	21 01	Bandstop loop
048	GSB9	23 09	increment k
049	X≤Y?	16-35	test for loop exit
050	RTN	24	
051	RCLi	36 45	a_k
052	RCL4	36 04	
053	CF0	16 22 00	
054	F1?	16 23 01	test for printorder
055	GTO6	22 06	
056	CLX	-51	
057	RCL5	36 05	
058	SF0	16 21 00	
059	*LBL6	21 06	
060	GSB8	23 08	calc & print elts.
061	GSB9	23 09	increment k
062	X≤Y?	16-35	test for loop exit
063	RTN	24	
064	RCLi	36 45	
065	RCL5	36 05	
066	SF0	16 21 00	
067	F1?	16 23 01	test for printorder
068	GTO6	22 06	
069	CLX	-51	
070	RCL4	36 04	
071	CF0	16 22 00	
072	*LBL6	21 06	
073	GSB8	23 08	calc & print elts.
074	GTO1	22 01	
075	*LBL8	21 08	calculate and print
076	×	-35	subroutine for
077	STO8	35 08	bandstop filters
078	F0?	16 23 00	
079	PRTX	-14	
080	RCL0	36 00	
081	X²	53	
082	×	-35	
083	1/X	52	
084	PRTX	-14	
085	F0?	16 23 00	
086	GTO6	22 06	
087	RCL8	36 08	
088	PRTX	-14	
089	*LBL6	21 06	
090	SPC	16-11	
091	RTN	24	
092	*LBLa	21 16 11	lowpass type 1
093	SPC	16-11	print heading
094	3	03	"31"
095	1	01	
096	PRTX	-14	
097	SPC	16-11	
098	CF0	16 22 00	
099	GSB7	23 07	calculate consts
100	GTO2	22 02	goto output rout.

050

REGISTERS

0	1	2	3	4	5	6	7	8	9
$2\pi f_c$	2πBW	R		used	used	n	k		

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
a_n	a_{n-1}	a_{n-2}	a_{n-3}	a_{n-4}	a_{n-5}	a_{n-6}	a_{n-7}	a_{n-8}	a_{n-9}

A	B	C	D	E	I
a_{n-10}	a_{n-11}	a_{n-12}			index

97 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
101	*LBLb	21 16 12	Lowpass Type 2
102	SPC	16-11	print headings
103	3	03	
104	2	02	"32"
105	PRTX	-14	
106	SPC	16-11	
107	CF0	16 22 00	lowpass filter
108	GSB7	23 07	change to type 2
109	RCL2	36 02	coefficients
110	X²	53	
111	ST÷4	35-24 04	
112	ST×5	35-35 05	
113	GTO2	22 02	goto output routine
114	*LBLd	21 16 14	Highpass Type 2
115	SPC	16-11	print heading
116	4	04	
117	2	02	"42"
118	PRTX	-14	
119	SPC	16-11	
120	SF0	16 21 00	highpass filter
121	GSB7	23 07	calc coeff's
122	GTO2	22 02	goto output routine
123	*LBLc	21 16 13	Highpass Type 1
124	SPC	16-11	print heading
125	4	04	
126	1	01	"41"
127	PRTX	-14	
128	SPC	16-11	
129	SF0	16 21 00	highpass filter
130	GSB7	23 07	calc coeff's
131	RCL2	36 02	
132	X²	53	
133	ST÷4	35-24 04	
134	ST×5	35-35 05	
135	*LBL2	21 02	lopass/hipass out.
136	GSB9	23 09	increment k
137	X≤Y?	16-35	test for loop exit
138	RTN	24	
139	RCLi	36 45	recall a_k
140	F0?	16 23 00	highpass?
141	1/X	52	if so form $1/a_k$
142	RCL5	36 05	scale element value
143	×	-35	
144	PRTX	-14	print element
145	GSB9	23 09	increment k
146	X≤Y?	16-35	test for loop exit
147	RTN	24	
148	RCLi	36 45	recall a_k
149	F0?	16 23 00	highpass?
150	1/X	52	if so form $1/a_k$
151	RCL4	36 04	scale element value
152	×	-35	
153	PRTX	-14	print element
154	GTO2	22 02	loop
155	*LBL7	21 07	type 1 routine
156	RCL2	36 02	R
157	RCL1	36 01	2πBW
158	÷	-24	
159	STO4	35 04	inductor scaling
160	RCL2	36 02	
161	X²	53	
162	÷	-24	
163	STO5	35 05	capacitor scaling
164	0	00	initialize k
165	STO7	35 07	
166	RTN	24	
167	*LBL9	21 09	increment k and test loop exit
168	1	01	
169	ST+7	35-55 07	
170	RCL7	36 07	
171	9	09	
172	+	-55	
173	STOI	35 46	
174	RCL7	36 07	
175	RCL6	36 06	
176	1	01	
177	+	-55	
178	RTN	24	

LABELS

A Store $w_0 = 2\pi f_0 \rightarrow R_0$	B Store $2\pi BW \rightarrow R_1$	C Store $R \rightarrow R_2$	D Bandstop type 1	E Bandstop Type 2
a Lowpass Type 1	b Lowpass Type 2	c Highpass Type 1	d Highpass Type 2	e
0 Bandstop Coef calc	1 Bandstop loop destin.	2 lopass/Hipass Loop return	3	4
5	6 local loop destination	7 Hi/Low pass coefficients	8 Bandstop output routine	9 increment k and test exit

FLAGS

0	used
1	used
2	
3	

SET STATUS

FLAGS	ON	OFF
0	☐	■
1	☐	■
2	☐	■
3	☐	■

TRIG	
DEG	■
GRAD	☐
RAD	☐

DISP	
FIX	☐
SCI	☐
ENG	■
n	3

Program Description I

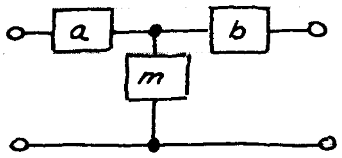
Program Title Y-Δ TRANSFORM FOR L,R, or C

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

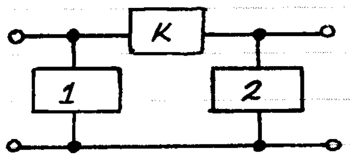
Program Description, Equations, Variables This program performs the Y-Δ transform for trios of resistors, inductors, or capacitors. These transformations find use wherever awkward or physically impractical element values result from electrical network design. The resistive transform is oftentimes used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

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

"Y" topology



"Δ" topology



for Capacitors:

Y → Δ

$$C_1 = C_a C_m / \Sigma C$$
$$C_2 = C_b C_m / \Sigma C$$
$$C_k = C_a C_b / \Sigma C$$
$$\Sigma C = C_a + C_b + C_m$$

Δ → Y

$$C_a = \Sigma CC / C_2$$
$$C_b = \Sigma CC / C_1$$
$$C_m = \Sigma CC / C_K$$
$$\Sigma CC = C_1 C_2 + C_2 C_K + C_1 C_K$$

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

Y → Δ

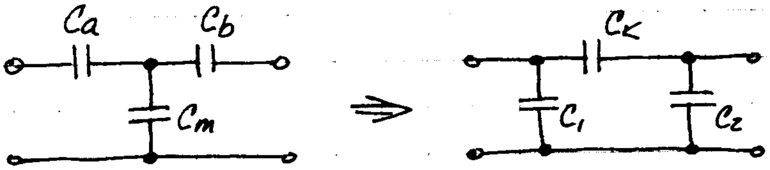
$$L_1 = \Sigma LL / L_b$$
$$L_2 = \Sigma LL / L_a$$
$$L_K = \Sigma LL / L_m$$
$$\Sigma LL = L_a L_b + L_b L_m + L_a L_m$$

Δ → Y

$$L_a = L_1 L_K / \Sigma L$$
$$L_b = L_2 L_K / \Sigma L$$
$$L_m = L_1 L_2 / \Sigma L$$
$$\Sigma L = L_1 + L_2 + L_K$$

Program Description II

Sketch(es) Convert the following Capacitor networks.



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

ΣC before xfm = 6 μF

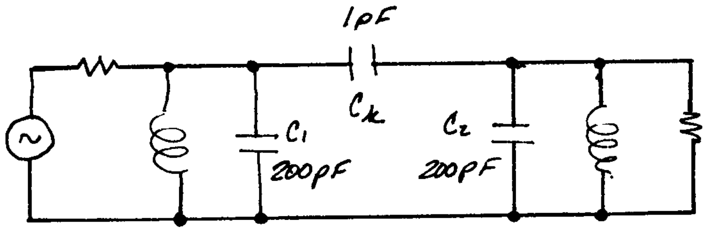
Solution(s) Enter data into program 1E-6 [A], 2E-6 [B], 3E-6 [C], elements are capacitors [f] [A]. to list input elements [f] [E]. To perform Y->Δ transform [D]*. To list transformed elements [f] [E]. The transformed element values are: C_1 = 0.333 μF, C_K = 0.5 μF, C_2 = 1.00 μF, and Σ C's = 1.833..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

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

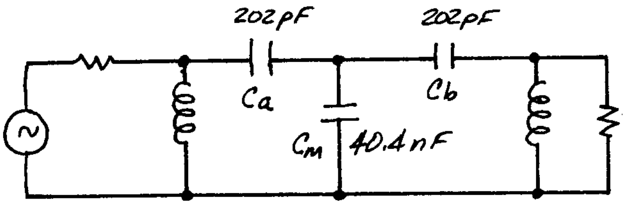
* [D] calls [f] [E] both before and after transformation. [f] [E] lists the currently stored element values.

A MORE PRACTICAL TRANSFORMATION EXAMPLE:

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



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




```
         ENG  )
         DSP3 )
200.-12  GSBA )  DATA
         GSBC )  ENTRY
  1.-12  GSBB )
         GSBa )
         GSBE )

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

        Δ→Y xfm

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

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

User Instructions

$Y \to \Delta$, $\Delta \to Y$ TRANSFORMATION				
C	L, R			print stored elements
element 1	element M	element 2	$Y \to \Delta$	$\Delta \to Y$

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

Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
			DATA ENTRY
001	*LBLA	21 11	ENTER ELEMENT 1 or a
002	STOA	35 11	
003	RTN	24	
004	*LBLB	21 12	ENTER ELEMENT k or m
005	STOB	35 12	
006	RTN	24	
007	*LBLC	21 13	ENTER ELEMENT 2 or b
008	STOC	35 13	
009	RTN	24	
010	*LBLa	21 16 11	CLEAR FLAG 0 TO INDICATE CAPACITORS
011	CF0	16 22 00	
012	RTN	24	
013	*LBLb	21 16 12	SET FLAG 0 TO INDICATE RESISTORS OR INDUCTORS
014	SF0	16 21 00	
015	RTN	24	
016	*LBLe	21 16 15	PRINT STORED ELEMENTS AND SUM OF STORED ELEMENTS
017	SPC	16-11	
018	RCLA	36 11	
019	PRTX	-14	
020	RCLB	36 12	
021	PRTX	-14	
022	+	-55	
023	RCLC	36 13	
024	PRTX	-14	
025	+	-55	
026	PRTX	-14	
027	SPC	16-11	
028	RTN	24	

STEP	KEY ENTRY	KEY CODE	COMMENTS
029	*LBLD	21 14	Y→Δ ROUTINE FOR CAPACITORS OR Δ→Y ROUTINE FOR RESISTORS AND INDUCTORS
030	GSBe	23 16 15	
031	F0?	16 23 00	
032	GTO0	22 00	
033	*LBL1	21 01	
034	RCLA	36 11	
035	RCLB	36 12	
036	+	-55	
037	RCLC	36 13	
038	+	-55	
039	STOD	35 14	
040	RCLA	36 11	
041	RCLB	36 12	
042	×	-35	
043	RCLD	36 14	
044	÷	-24	
045	STOE	35 15	
046	RCLA	36 11	
047	RCLC	36 13	
048	×	-35	
049	RCLD	36 14	
050	÷	-24	
051	RCLE	36 15	
052	STOA	35 11	
053	R↓	-31	
054	STOE	35 15	
055	RCLB	36 12	
056	RCLC	36 13	
057	×	-35	
058	RCLD	36 14	
059	÷	-24	
060	STOC	35 13	
061	RCLE	36 15	
062	STOB	35 12	
063	GTOe	22 16 15	

REGISTERS

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

A	B	C	D	E	I
ELEMENT 1 or a	ELEMENT k or m	ELEMENT 2 or b	ΣX or ΣXX x = L, R or C	used	

Program Listing II

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

LABELS

A ELEMENT 1or a ENTRY	B ELEMENT k or M ENTRY	C ELEMENT 2 or b ENTRY	D Y→Δ x/m	E Δ→Y x/m
a set CAPACITOR	b set INDUCTOR or RESISTOR	c	d	e PRINT ELEMENTS
0 L or R DESTINATION	1 L or R DESTINATION	2	3	4
5	6	7	8	9

FLAGS

0	0 = CAP "1" = L or R
1	
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	■	□	DEG	■	FIX	■
1	□	■	GRAD	□	SCI	□
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

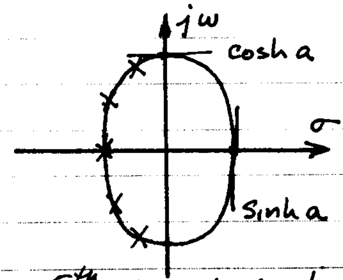
Address 6875 Sabado Tarde Road

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

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



5th order pole locations

pole locations:

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

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

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

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

Program Description I

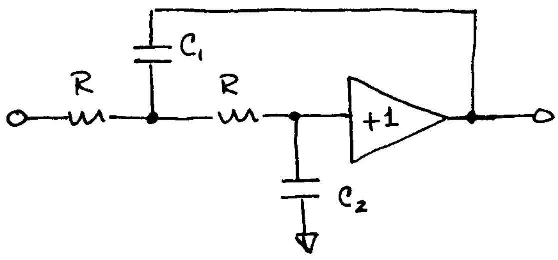
Each pole pair location may be expressed in terms of real and imaginary parts which is the Cartesian coordinate system, or the polar coordinate system may be used, in which case the pole pair location may be expressed by a natural frequency, w_n, and a Q, or quality factor. The relation between these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

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

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

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

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



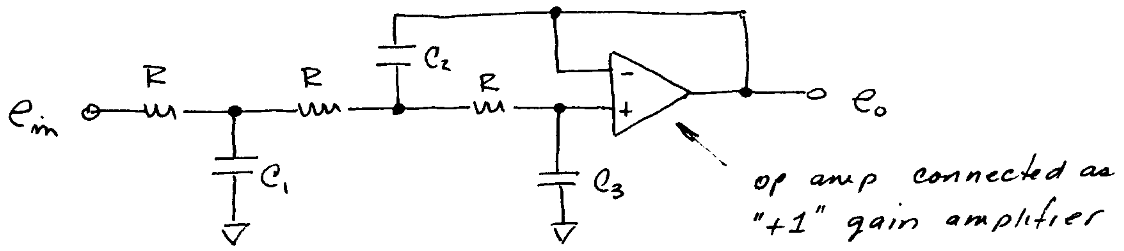
$$C_1 = \frac{2Q}{\omega_n R} \quad ; \quad C_2 = \frac{C_1}{4Q^2}$$

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

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

Program Description I

3rd Order filter section



$$e_o/e_{in} = \frac{1}{Cs^3 + Bs^2 + As + 1} = \frac{1}{\frac{s^2}{\omega_n^2} + \frac{s}{\omega_n Q} + 1} \cdot \frac{1}{\tau s + 1}$$

second order pole pair — real pole

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

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

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

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

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

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

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

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

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

Program Description I

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

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

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

once C_2 is obtained, the other capacitor values follow

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

and

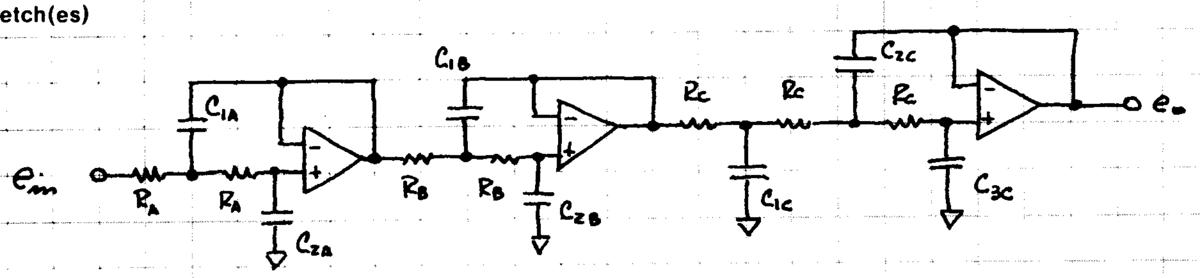
$$C_3 = \frac{C}{C_1 C_2}$$

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

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

Program Description II

Sketch(es)



Sample Problem(s)

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

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

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

Reference(s)

Program Description

```
      1. GSBA   ripple in dB
      7. GSBB   filter order
  1.+04 GSBC    resistance level, ohms = RA = RB = RC
  1000. GSBE    freq where filter is ε dB (1dB) down

 first resonator (second order)
6.26014+03  ***   ωn
10.8987+00  ***   Q
348.192-09  ***   C1A
732.846-12  ***   C2A
 second resonator (second order)
5.07911+03  ***   ωn
3.15586+00  ***   Q
124.268-09  ***   C1B
3.11935-09  ***   C2B
third resonator (third order)
3.01626+03  ***   ωn }
1.29693+00  ***   Q  }  second order pole pair
1.29066+03  ***   σ  <-- load second card here & press [A]
84.2120-09  ***   C1C
161.111-09  ***   C2C
6.27702-09  ***   C3C
```

User Instructions

Chebychev Active L.P. Filters & Pole locations, CARD #1				
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				
2	KEY IN PASSBAND RIPPLE IN dB	ϵ_{dB}		A	
3	KEY IN FILTER ORDER	n		B	
4	KEY IN DE-NORMALIZATION RESISTANCE	R		C	
5	START PROGRAM EXECUTION				
	a) IF FILTER IS TO BE -3dB DOWN AT CUTOFF FREQUENCY	f_{CUTOFF}		D	SEE E
	b) IF FILTER IS TO BE $-\epsilon$dB DOWN AT CUTOFF FREQUENCY	f_{CUTOFF}		E	ω_{n1}
					Q_1
					C_{11}
					C_{21}
					ω_{n2}
					Q_2
					C_{12}
					C_{22}
					⋮
	* IF FILTER ORDER IS ODD, .111111111 WILL BE DISPLAYED WHICH SIGNALS THE OPERATOR TO LOAD THE SECOND CARD AND PRESS [A]				.111111111*
					⋮
			EVEN ORDER		ω_{nn}
					Q_n
					C_{1n}
					C_{2n}
			ODD ORDER		ω_{nn}
					Q_n
					σ_n
					C_{1n}
					C_{2n}
					C_{3n}

User Instructions

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

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

97 Program Listing I

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

REGISTERS

0	1	2	3	4	5	6	7	8	9
2k-1	2Q	a or ω_n	1 or ω_{3dB}		1/ε	R	ω_k	σ_k	used

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
n	εdB	sinh a	cosh a	π/2n	

97 Program Listing II

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

LABELS

A ENTER EdB	B ENTER n	C ENTER R	D f_{-3dB} start	E f_{EdB} start
a	b	c	d	e
0	1 Wn & Q calc	2 odd order output	3 even order output	4
5	6	7	8	9

FLAGS

0	n even
1	
2	P≥S used. add # times
3	

SET STATUS

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

97 Program Listing I

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

REGISTERS

0	1	2	3	4	5	6	7	8	9
							ω_k	σ_k	

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
a, C_1	b	c	B	A	D=4C-2AB	p	q	r	C_2

A	B	C	D	E	I
		Sinh a			

97 Program Listing II

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

LABELS

A	B	C	D	E
START				
a	b	c	d	e
0	1 output subroutine	2	3	4
5	6	7	8	9

FLAGS

0	
1	
2	PZS odd # of times
3	

SET STATUS

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

NOTES

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