

FilterCAD User's Manual, Version 1.00

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PART 1—GETTING STARTED

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WHAT IS FILTERCAD?

FilterCAD is a computer-aided design program for use in conjunction with the Linear Technology Corporation family of switched-capacitor filter i.c.'s. Devices supported by this version of FilterCAD include the LTC1059, 1059A, 1060, 1060A, 1061, 1061A, 1064, 1064A and 1164. Future Linear Technology Corporation devices may be added when available by means of the FilterCAD Device Parameter Editor (see Appendix 1).

FilterCAD is designed to help users without special expertise in filter design to design good filters with a minimum of effort. It can also help experienced filter designers achieve better results by providing the ability to play "what if" with the values and configuration of various components.

With FilterCAD, you can design any of the four major filter types (lowpass, highpass, bandpass, and notch), with Butterworth, Chebyshev, Elliptic, or custom-designed response characteristics. (Bessel filters can be realized by manually entering pole and Q values, but FilterCAD cannot synthesize a Bessel response in this version.) FilterCAD is limited to designs which can be achieved by cascading state-variable second-order sections. FilterCAD plots amplitude, phase and group-delay graphs, selects appropriate devices and modes, and calculates resistor values. Device selection, cascade order, and modes can be edited by the user.

LICENSE AGREEMENT/DISCLAIMER

This copy of FilterCAD is provided as a courtesy to the customers of Linear Technology Corporation. It is licensed for use in conjunction with Linear Technology Corporation products only. The program is not copy protected and you may make copies of the program as required, provided that you do not modify the program, and that said copies are used only with Linear Technology Corporation products.

While we have made every effort to ensure that FilterCAD operates in the manner described in this manual, we do not guarantee operation to be error free. Upgrades, modifications, or repairs to this program will be strictly at

the discretion of Linear Technology Corporation. If you encounter problems in installing or operating FilterCAD, you may obtain technical assistance by calling our applications department, at (408) 432-1900, between 8:00 a.m. and 5:00 p.m. Pacific time, Monday through Friday. Because of the great variety of IBM-compatible computer systems, operating-system versions, and peripherals currently in use, we do not guarantee that you will be able to use FilterCAD successfully on all such systems. If you are unable to use FilterCAD, Linear Technology Corporation does guarantee to provide design support for LTC filter products by whatever means necessary.

Linear Technology Corporation (LTC) makes no warranty, either expressed or implied, with respect to the use of FilterCAD or its documentation. Under no circumstances will LTC be liable for damages, either direct or consequential, arising from the use of this product or from the inability to use this product, even if we have been informed in advance of the possibility of such damages.

INVENTORY

Please check to be sure you have received the following items:

This Manual
 FilterCAD Program Disk
 LTC Filter Application Notes and Data Sheets may be included or, if they are not, may be requested from LTC.

The FilterCAD Diskette

Your FilterCAD distribution diskette includes the following files. If, after installing the program, you have difficulty in running FilterCAD, check your disk to be sure all of the necessary files are present.

README.DOC	(Optional) if present, includes updated information on FilterCAD not included in this manual
INSTALL.BAT	Automatic installation program — installs FilterCAD on hard drive
FCAD.EXE	Main program file for FilterCAD

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FCAD.OVR	Overlay file for FilterCAD — used by FCAD.EXE
FCAD.ENC	Encrypted copyright protection file — DO NOT TOUCH!
FDPF.EXE	Device-parameter file editor — used to update FCAD.DPF (see Appendix 1)
FCAD.DPF	Device-parameter file — holds data for all device types supported by FilterCAD
ATT.DRV	AT&T graphics adapter driver
CGA.DRV	IBM CGA or compatible graphics driver
EGAVGA.DRV	EGA and VGA graphics drivers
HERC.DRV	Hercules monochrome graphics driver
ID.DRV	Identification file for all driver specifications

A 3 1/2" diskette available upon special request contains the following files in addition to those just mentioned:

IBM8514.DRV	IBM8514 color graphics adapter driver
PC3270.DRV	IBM PC3270 color graphics adapter driver

Note: Once you have configured FilterCAD and selected your display type, you can delete unnecessary drivers if you need to conserve disk space. (Be sure not to delete any drivers from your original FilterCAD distribution diskette.)

Before You Begin

Please check the FilterCAD program disk to see if it contains the README.DOC file. This file, if present, will contain important information about FilterCAD not included in this manual. Please read this file before attempting to install and use FilterCAD. To display the README file on your screen, place the FilterCAD diskette in drive A and type:

```
TYPE    README.DOC    [Enter]
```

Press

```
[Ctrl] S
```

to pause scrolling. Press any key to resume scrolling. To print a hardcopy of the README file on your printer type:

```
TYPE    README.DOC >PRN    [Enter]
```

HARDWARE REQUIREMENTS

FilterCAD runs on an IBM PC, XT, AT, or PS/2, or a compatible system, equipped with one floppy drive or one hard drive and one floppy drive, at least 256k bytes of system memory, an appropriate graphics adapter and monitor, and DOS 2.0 or later. A list of the graphics adapters and modes supported by FilterCAD will be found in the "Configuration" section. FilterCAD is a calculation-intensive program, and should, therefore, be run on the most powerful system available. A floating-point math coprocessor (8087, 80287, or 80387, as appropriate for your system) is not required, but will significantly increase the operating speed of the program.

INSTALLATION

Floppy Disk Systems

Use the DOS DISKCOPY command to make a copy of the FilterCAD distribution disk. Place a diskette with the DOS DISKCOPY.COM program in drive A and type:

```
DISKCOPY  A:    B:    [Enter]
```

Following the messages that appear on your screen, place the FilterCAD distribution disk in drive A, place a blank floppy disk in drive B, and press any key to begin copying. When the copy is completed, put the original FilterCAD disk away in a safe place, and label your copy. You will use your copy to run FilterCAD.

Note: If you have only one floppy drive, DISKCOPY will prompt you when to swap diskettes. Just follow the messages that appear on the screen.

Hard Disk Systems

To install FilterCAD on a hard disk system, you should first make a floppy disk backup of the FilterCAD distribution disk, as indicated. Then, put your working copy of the FilterCAD diskette in drive A and type:

```
INSTALL N: (path) (Enter)
```

Where

```
"N:"
```

is the drive letter and

```
(path)
```

is an optional path specification. The INSTALL.BAT program will create a sub-directory called "FCAD" on the drive and below the optional path you have specified, and copy the FilterCAD program files into that directory. For example, if you typed

```
INSTALL C: (Enter)
```

the program files will be installed in C:\FCAD. If you typed

```
INSTALL C: \ FILTERS (Enter)
```

the program files will be installed in C:\FILTERS\FCAD.

FilterCAD is now installed on your hard disk and ready to run.

Note: If the directory you specify already exists, the install program will issue an error message saying that it was unable to create the specified directory. It will then copy the FilterCAD files into the existing directory, overwriting the earlier version of FilterCAD. However, before installing this version of FilterCAD over an existing version, you should delete the earlier version of FCAD.CFG from your hard disk to avoid problems.

STARTING AND CONFIGURING FILTERCAD

To start FilterCAD, place your working copy of the FilterCAD diskette in drive A or log on to the directory on your hard disk where FilterCAD's program files have been installed, and type:

```
FCAD (Enter)
```

When you see FilterCAD's sign-on screen, press

```
(Enter)
```

again to start the program. When you run FilterCAD for the first time, select item 6 on the MAIN MENU, "CONFIGURE FilterCAD," before attempting to use the program. This will open the HARDWARE CONFIGURATION MENU, which offers the following eight options:

1. Install DISPLAY
 2. Install PRINTER
 3. Install PLOTTER
 4. Install MOUSE
 5. Configure I/O PORTS
 6. Configure DISPLAY PARAMETERS
 7. Set PATH to DRIVERS
9. RETURN to MAIN MENU

Installing the Display

The first step is to tell FilterCAD what video display adapter is installed in your system and what graphics mode you wish to use. To access the DISPLAY INSTALLATION MENU, press

```
1
```

The DISPLAY INSTALLATION MENU offers fourteen options, supporting all of the popular PC display adapters, including the IBM Color Graphics Adapter (CGA), the MCGA (the built-in graphics controller in IBM's PS/2 models 25 and 30), the Enhanced Graphics Adapter (EGA), the Video Graphics Array (VGA, the built-in graphics controller in IBM's PS/2 models 50-80, also available as an add-in card for PC/XT/AT family machines), Hercules Monochrome Graphics, the AT&T Graphics Adapter, and the IBM 8514 Graphics Adapter (IBM's high resolution graphics add-in for the PS/2 models 50-80). To install the driver for your display adapter and desired graphics mode, simply type the number of your selection and press

```
(Enter)
```

Several of the supported display adapters offer more than one option for different resolutions or color selections. The resolution and number of colors you will be able to obtain from a particular display adapter may depend on

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the type of monitor connected to it. For example, the Enhanced Graphics Adapter will display 640 pixels by 200 lines with 16 colors on a standard RGB monitor (option 4), 640 pixels by 350 lines with 16 colors on an enhanced RGB monitor (item 5), or 640 pixels by 350 lines in monochrome on a TTL monochrome monitor (item 6). Obviously it is desirable to choose the highest resolution and greatest color selection available from your system. If you are uncertain what option to select for your particular monitor/display adapter combination, consult the documentation for your computer system, display adapter, and/or monitor.

Note: When you install your display and exit back to FilterCAD's main menu, you will be asked whether you want to save your changes to the FCAD.CFG file. Answer "YES." This will create the configuration file which will be used every time you start FilterCAD.

Installing Your Printer and Plotter

FilterCAD has been equipped with a text printer driver for a standard-ASCII text printer, which is used for printing reports, and a plotter driver for an HPGL-compatible plotter. These selections cannot be modified by the user. In addition, you can select a printer driver for a graphics screen dump. Press

2

to access the printer installation menu. The options at this time are limited to the Epson FX-80 or a compatible dot-matrix printer, the Hewlett-Packard ThinkJet, and the Hewlett-Packard LaserJet or a compatible laser printer. The last can be configured to print at a number of different resolutions, including 75, 100, 150, or 300 dots-per-inch. Note that FilterCAD performs a true pixel-for-pixel screen dump, so the size of the image depends on the resolution. At 300 d.p.i., the image is approximately the size of a large postage stamp.

Configuring Display Parameters

Item 6 on the HARDWARE CONFIGURATION MENU, "Configure Display Parameters" has two functions: "Change SCREEN COLORS," and "Change GRAPH Window." The first option, obviously, allows you to select the colors used for the various text messages and graphic

elements displayed by the program. Of course, if you are using a display option that only supports two colors (e.g., the IBM Color Graphics Adapter or Hercules Monochrome Graphics) this item will not allow you to select different colors for the graphic elements, but it will allow you to select different attributes (underline, high-intensity, reverse-video, etc.) for the different classes of text messages. Use the arrow keys to select the items that you wish to modify, and use the

F

and

B

keys to step through the available color options. Press

D

if you wish to restore the default colors (the colors that were displayed when you started the program). Press

ESC

to exit the COLOR CONFIGURATION MENU and save your changes. When you configure FilterCAD for the first time, it is recommended that you select the colors for the text messages only. Delay changing the options for the graphic elements until you have had a chance to explore the program and see how the various graphic elements interact.

The second option under Configure DISPLAY Parameters, "Change GRAPH Window," allows you to modify the frequency and gain ranges of the filter frequency response graphs generated by FilterCAD, as well as the number of data points that will be plotted. Whereas most of the configuration settings can be set once and then forgotten, the parameters of the graph window may have to be modified regularly as you design different types of filters with different frequency ranges. Until you have explored the graphing features of FilterCAD, you should probably leave the default parameters of the graph window unmodified.

WHAT IS A FILTER?

A filter is a circuit that selectively passes a certain range of the frequencies present at its input to its output, while blocking (attenuating) other frequencies. Filters are normally described in terms of the frequencies that they pass.

Most filters conform to one of four common types. Low-pass filters pass all frequencies below a specified frequency (called the cutoff frequency) and progressively attenuate frequencies above the cutoff frequency. High-pass filters do exactly the opposite; they pass frequencies above the cutoff frequency while progressively attenuating frequencies below the cutoff frequency. Bandpass filters pass a band of frequencies around a specified center frequency, attenuating frequencies above and below. Notch or bandstop filters attenuate the frequencies around the center frequency, passing frequencies above and below. The four basic filter types are illustrated in Figures 1.1-1.4. There are also allpass filters, which, not surprisingly, pass all of the frequencies present at their input.¹ In addition, it is possible to create filters with more complex responses which are not easily categorized.

The range of frequencies that a filter passes is known, logically enough, as its "passband." The range of frequencies that a filter attenuates is known as its "stopband." Between the passband and stopband is the "transition region." An ideal filter might be expected to pass all of the frequencies in its passband without modification while infinitely attenuating frequencies in its stopband. Such a response is shown in Figure 1.5. Regrettably, real-world filters do not meet these imaginary specifications. Different types of filters have different characteristics, less-than-infinite rates of attenuation vs. frequency in the

Note 1: While allpass filters don't affect the relative amplitudes of signals with different frequencies, they do selectively affect the phase of different frequencies. This characteristic can be used to correct for phase shifts introduced by other devices, including other types of filters. FilterCAD cannot synthesize allpass filters.

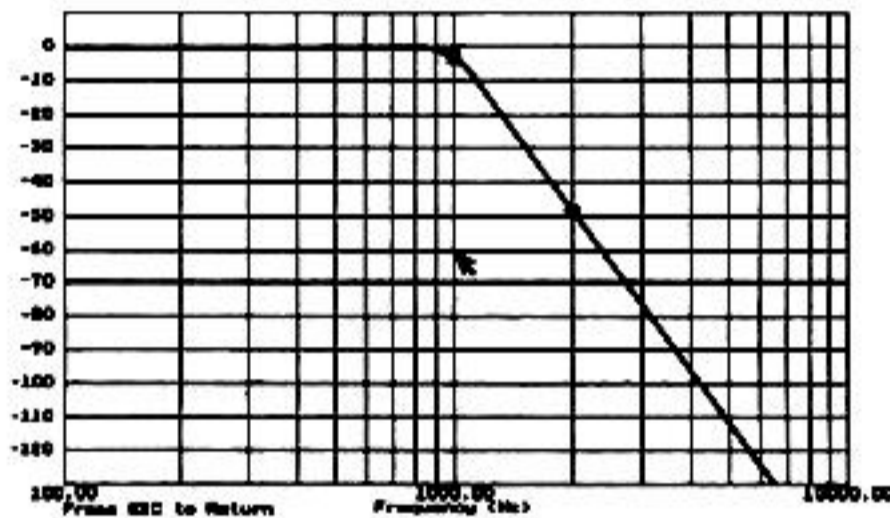


Figure 1.1. Lowpass Response

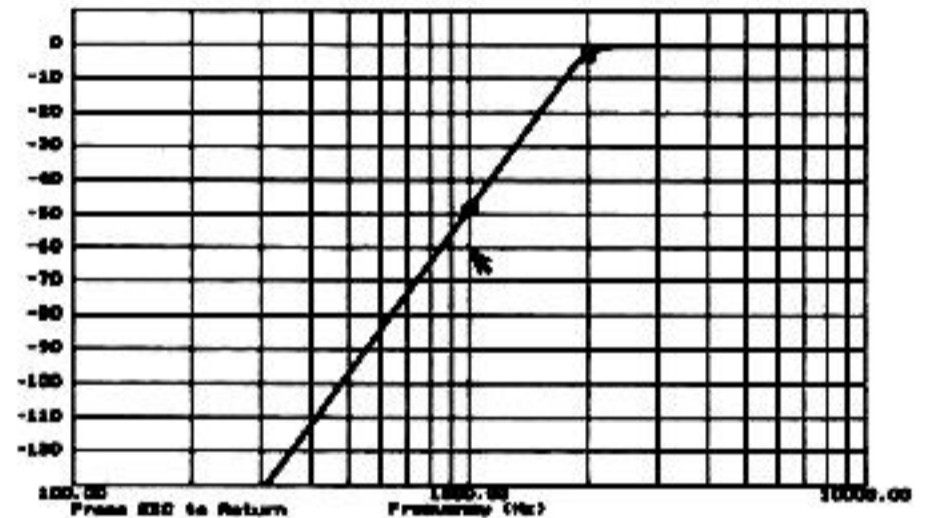


Figure 1.2. Highpass Response

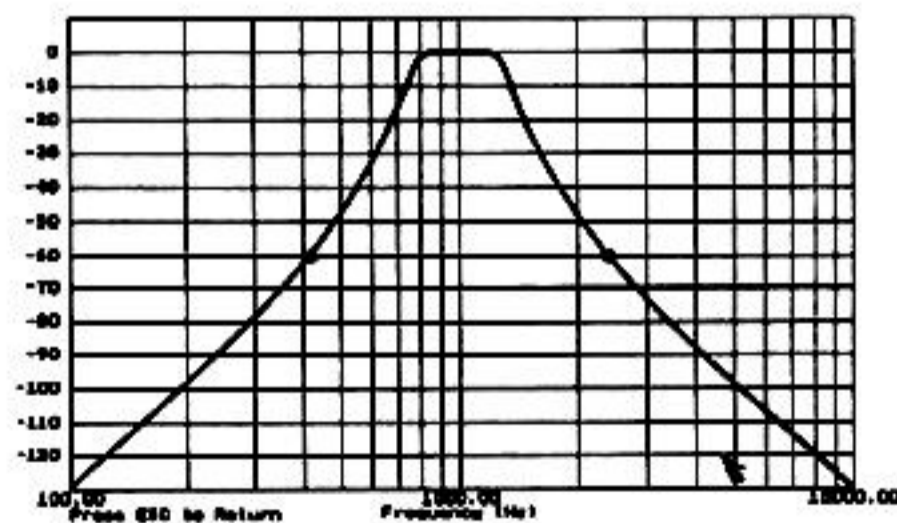


Figure 1.3. Bandpass Response

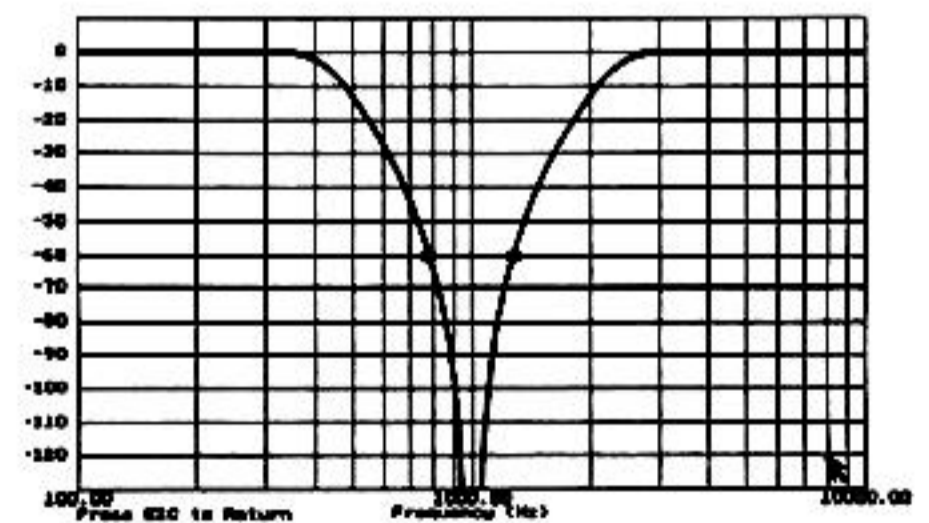


Figure 1.4. Notch Response

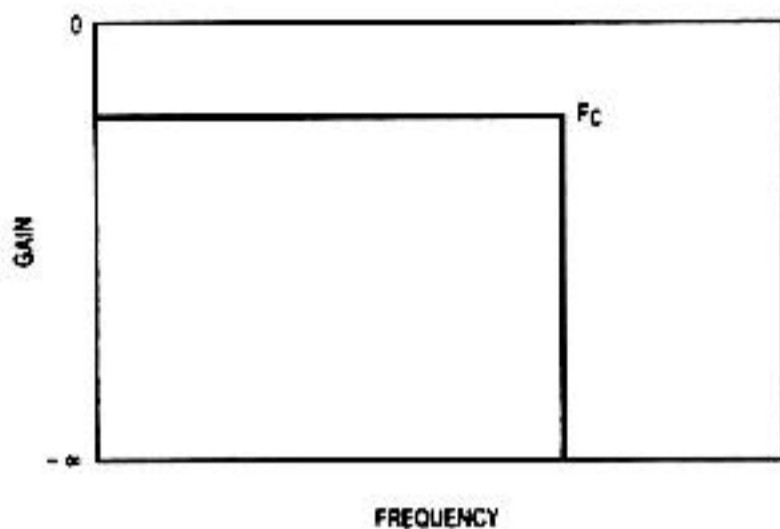


Figure 1.5. Ideal Lowpass Response

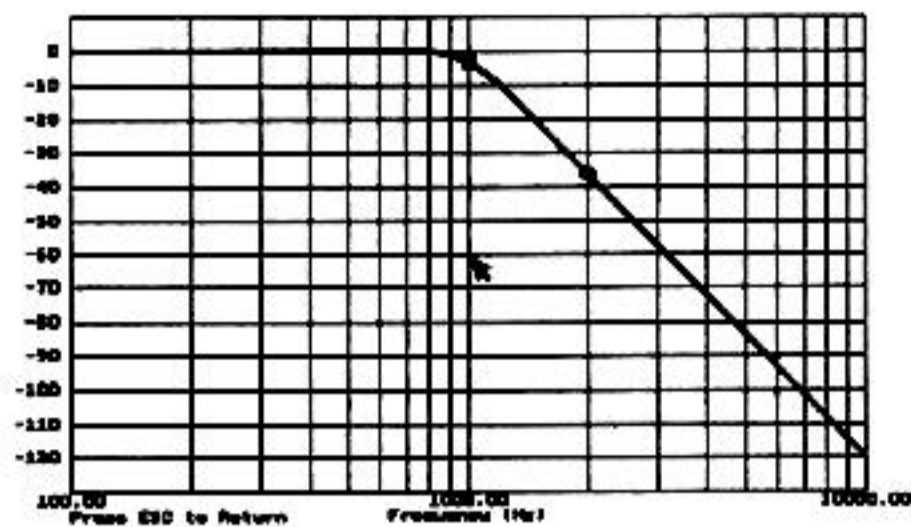


Figure 1.6. 6th Order Butterworth Lowpass Response

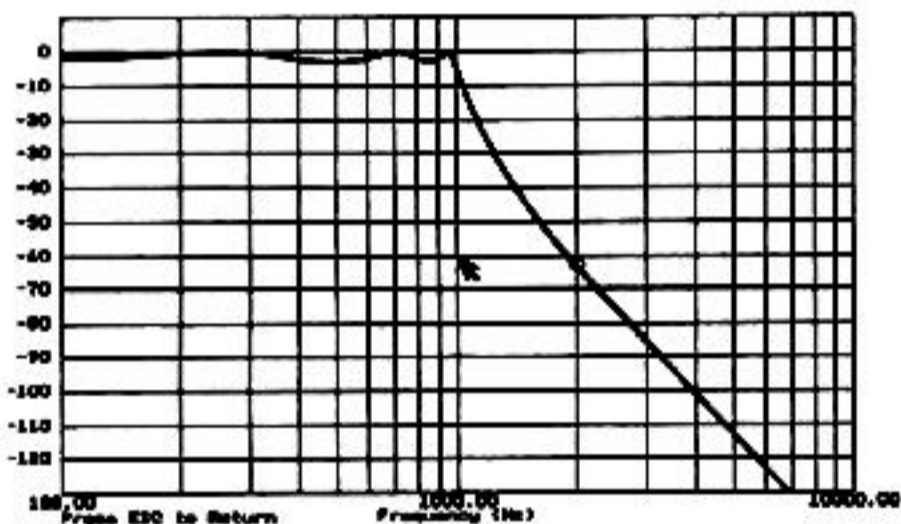


Figure 1.7. 6th Order Chebyshev Lowpass Response

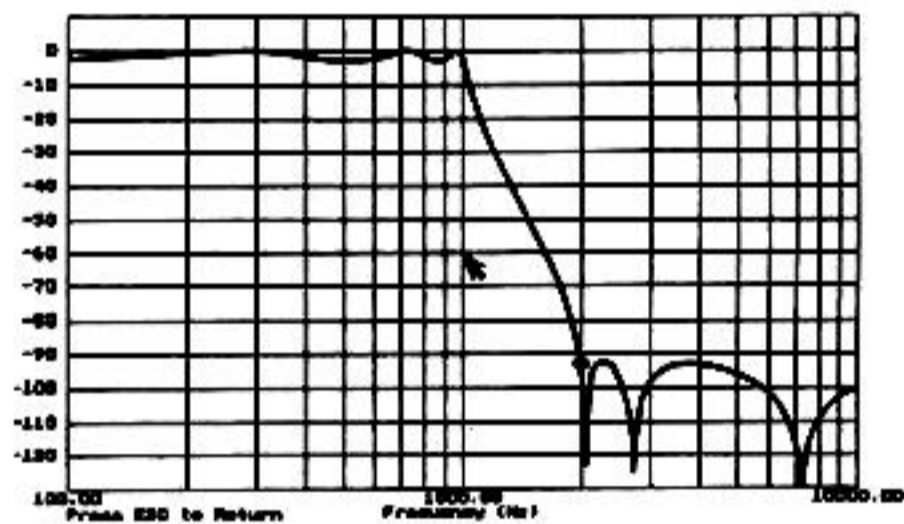


Figure 1.8. 6th Order Elliptic Lowpass Response

transition region. In other words, the amplitude response of a given filter has a characteristic slope. Frequencies in the passband may also be modified, either in amplitude ("ripple") or in phase. Real-world filters all represent compromises: steepness of slope, ripple, and phase shift (plus, of course, cost and size).

FilterCAD permits the design of filters with one of three response characteristics (plus custom responses). These three response types, which are known as "Butterworth," "Chebyshev," and "Elliptic," represent three different compromises among the previously described characteristics. Butterworth filters (Figure 1.6) have the optimum flatness in the passband, but have a slope that rolls off more gradually after the cutoff frequency than the other two types. Chebyshev filters (Figure 1.7) can have a steeper initial roll off than Butterworths, but at the expense of more than 0.4dB of ripple in the passband. Ellip-

tic filters (Figure 1.8) have the steepest initial roll off of all, but exhibit ripple in both the passband and the stopband. Elliptic filters have higher Q's which may (if not carefully implemented) translate to a noisier filter. These high Q's have made elliptic filters difficult to implement with active RC filters because of the increased stability and center frequency accuracy requirements. Elliptic filters can be implemented with SCF's due to their inherently better stabilities and center frequency accuracies when compared to active RC filters. Chebyshev and elliptic designs can achieve greater stopband attenuation for a given number of 2nd order sections than can Butterworths.

Filters are typically built up from basic building blocks known as 1st order and 2nd order sections. Each LTC filter contains circuitry which, together with an external clock and a few resistors, closely approximates 2nd order filter functions. These are tabulated in the frequency domain.

1. **Bandpass function:** available at the bandpass output pin, refer to Figure 1.9.

$$G(s) = H_{OBP} \frac{s\omega_0/Q}{s^2 + (s\omega_0/Q) + \omega_0^2}$$

H_{OBP} = Gain at $\omega = \omega_0$

$f_0 = \omega_0/2\pi$; f_0 is the center frequency of the complex pole pair. At this frequency, the phase shift between input and output is -180° .

Q = Quality factor of the complex pole pair. It is the ratio of f_0 to the -3dB bandwidth of the 2nd order bandpass function. The Q is always measured at the filter BP output.

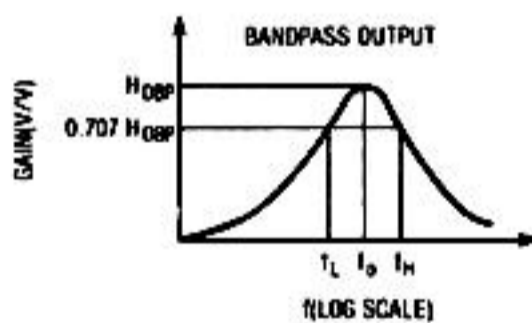
2. **Lowpass function:** available at the LP output pin, refer to Figure 1.10.

$$G(s) = H_{OLP} \frac{\omega_0^2}{s^2 + s(\omega_0/Q) + \omega_0^2}$$

H_{OLP} = DC gain of the LP output.

3. **Highpass function:** available only in mode 3 at the HP output pin, refer to Figure 1.11.

$$G(s) = H_{OHP} \frac{s^2}{s^2 + s(\omega_0/Q) + \omega_0^2}$$

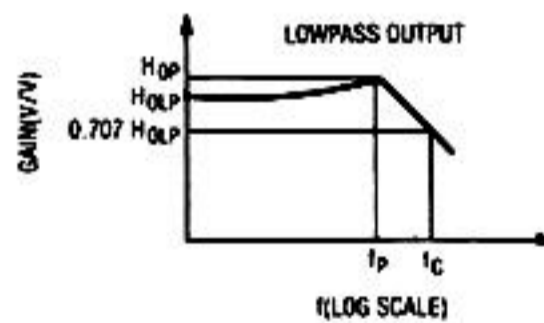


$$Q = \frac{f_0}{f_H - f_L} \quad f_0 = \sqrt{f_L f_H}$$

$$f_L = f_0 \left(\frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1} \right)$$

$$f_H = f_0 \left(\frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1} \right)$$

Figure 1.9. 2nd Order Bandpass Section

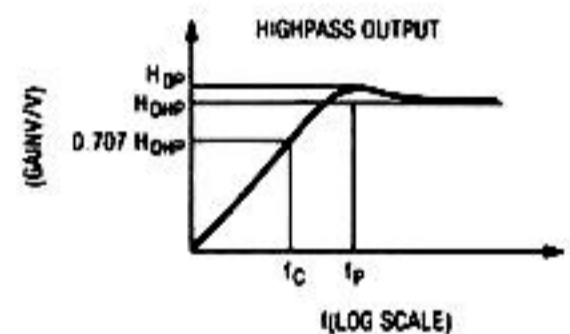


$$f_c = f_0 \times \sqrt{\left(1 - \frac{1}{20Q^2}\right) + \sqrt{\left(1 - \frac{1}{20Q^2}\right)^2 + 1}}$$

$$f_p = f_0 \sqrt{1 - \frac{1}{20Q^2}}$$

$$H_{OP} = H_{OLP} \times \frac{1}{Q \sqrt{1 - \frac{1}{40Q^2}}}$$

Figure 1.10. 2nd Order Lowpass Section



$$f_c = f_0 \times \left[\sqrt{\left(1 - \frac{1}{20Q^2}\right) + \sqrt{\left(1 - \frac{1}{20Q^2}\right)^2 + 1}} \right]^{-1}$$

$$f_p = f_0 \times \left[\sqrt{1 - \frac{1}{20Q^2}} \right]^{-1}$$

$$H_{OP} = H_{OHP} \times \frac{1}{Q \sqrt{1 - \frac{1}{40Q^2}}}$$

Figure 1.11. 2nd Order Highpass Section

H_{OHP} = gain of the HP output for $f = \frac{f_{CLK}}{2}$

4. **Notch function:** available at the N output for several modes of operation.

$$G(s) = (H_{ON2}) \frac{(s^2 + \omega_n^2)}{s^2 + s(\omega_0/Q) + \omega_0^2}$$

H_{ON2} = gain of the notch output for $f = \frac{f_{CLK}}{2}$

H_{ON1} = gain of the notch output for $f = 0$

$f_n = \omega_n/2\pi$; f_n is the frequency of the notch occurrence.

These sections are cascaded (the output of one section fed to the input of the next) to produce higher-order filters which have steeper slopes. Filters are described as being of a certain "order," which corresponds to the number and type of cascaded sections they comprise. For example, an 8th order filter would require four cascaded 2nd order sections, whereas a 5th order filter would require two 2nd order sections and one 1st order section. (The order of a filter also corresponds its number of poles, but an explanation of poles is outside the scope of this manual.)

PART 2—THE BASIC STEPS

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STEP ONE, THE BASIC DESIGN

The first item on FilterCAD's MAIN MENU is "DESIGN Filter." To access the DESIGN Filter screen, press

[Enter]

On the DESIGN Filter screen, you make several basic decisions about the type of filter you're going to design. First, you must select your basic filter type (lowpass, highpass, bandpass, or notch). Press the

Spacebar

to step through the options. When the filter type that you want is displayed, press

[Enter]

Next, you must select the type of response characteristic you want (Butterworth, Chebyshev, Elliptic, or Custom). Again, use the

Spacebar

to step through the options and press

[Enter]

when the response type you want is displayed.

Next, you will enter the most important parameters for your filter. Exactly what these parameters will be depends on the type of filter you have chosen. If you have selected

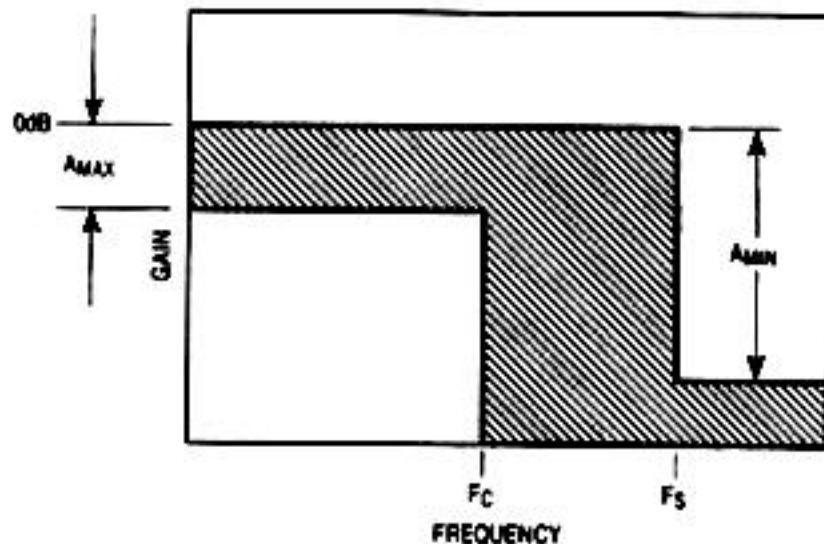


Figure 2.1. Lowpass Design Parameters: A_{MAX} = Maximum Passband Ripple, F_C = Corner Frequency, F_S = Stopband Frequency, A_{MIN} = Stopband Attenuation

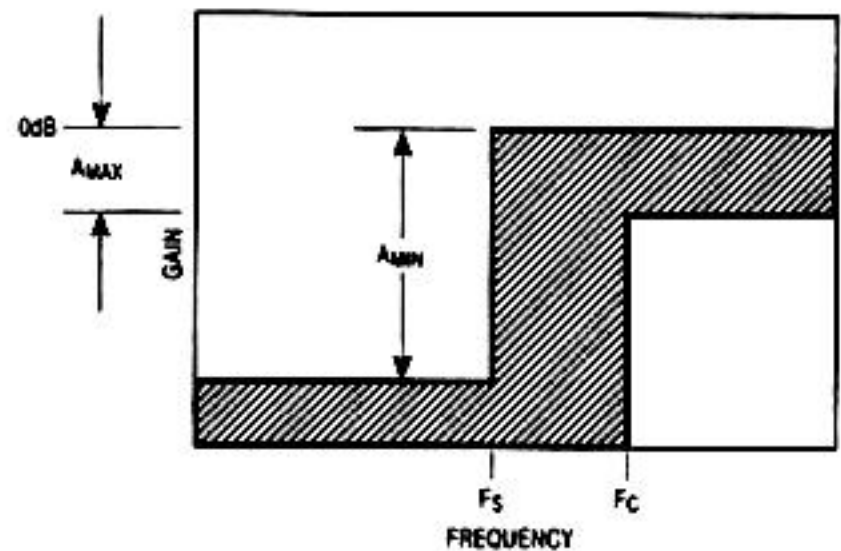


Figure 2.2. Highpass Design Parameters: A_{MAX} = Maximum Passband Ripple, F_C = Corner Frequency, F_S = Stopband Frequency, A_{MIN} = Stopband Attenuation

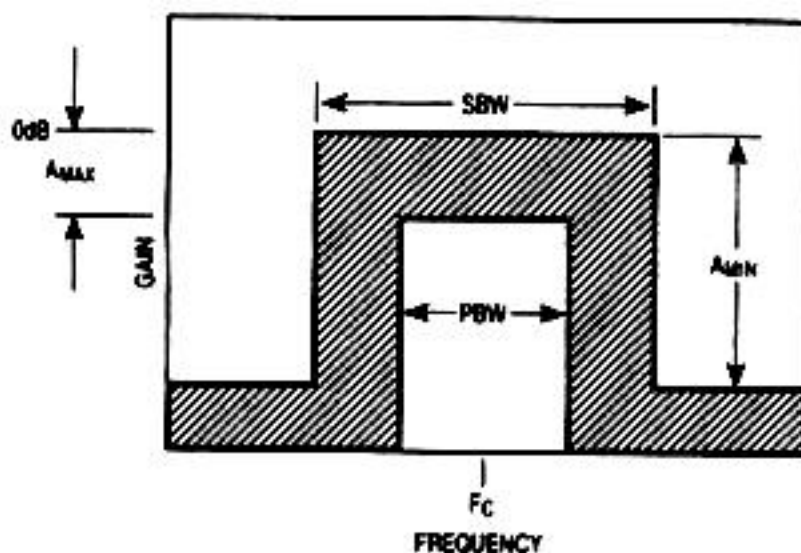


Figure 2.3. Bandpass Design Parameters: A_{MAX} = Maximum Passband Ripple, F_C = Center Frequency, PBW = Pass Bandwidth, SBW = Stop Bandwidth, A_{MIN} = Stopband Attenuation

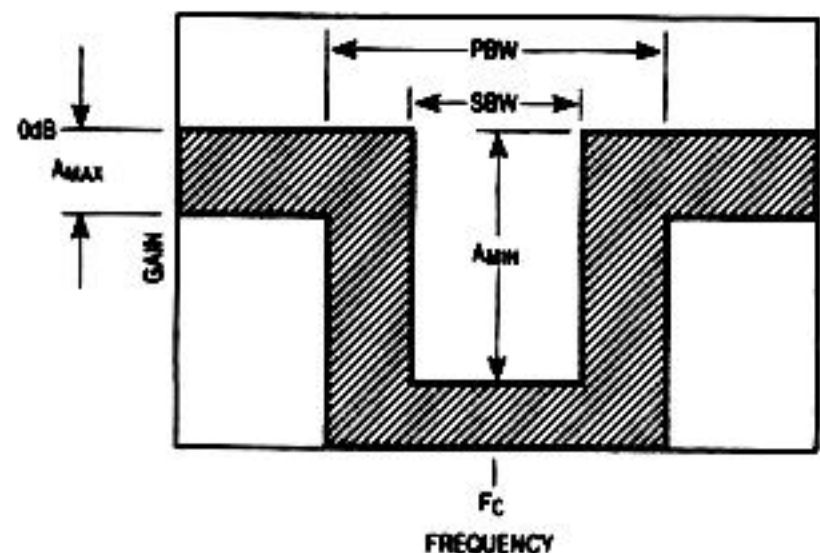


Figure 2.4. Notch Design Parameters: A_{MAX} = Maximum Passband Ripple, F_C = Center Frequency, PBW = Pass Bandwidth, SBW = Stop Bandwidth, A_{MIN} = Stopband Attenuation

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lowpass or highpass, you must enter the maximum passband ripple, in dB (must be greater than zero, or, in the case of Butterworth response, must be 3dB); the stopband attenuation, in dB; the corner frequency (also known as the cutoff frequency), in Hz; and the stopband frequency. If you chose a bandpass or notch filter, you must enter the maximum passband ripple and the stopband attenuation, followed by the center frequency, in Hz; the pass bandwidth, in Hz; and the stop bandwidth, in Hz. (The meanings of these various parameters in the different design contexts are illustrated in Figures 2.1-2.4.) If you chose a custom response, you're in an entirely different ball game, which will be described later.

Type in the parameters for your chosen filter, pressing

[Enter]

after each parameter. If you want to go back and alter one of the parameters you have previously entered, use the

Up-Arrow

and

Down-Arrow

keys to move to the appropriate location and retype the parameter. When you have entered all of the correct parameters, move the cursor to the last parameter in the list and press

[Enter]

FilterCAD will now calculate and display additional parameters of the filter you have designed, including its order, actual stopband attenuation, and gain, and will display a list of the 2nd order and 1st order sections needed to realize the design, along with their F_0 , Q , and F_n values (as appropriate). These numbers will be used later to implement your filter design and calculate resistor values.

FilterCAD will, in many cases, prevent you from entering inappropriate values. For instance, in the case of a lowpass filter, the program will not permit you to enter a stopband frequency that is lower than the corner frequency. Similarly, in the case of a highpass filter, the stopband frequency must be lower than the corner frequency. In addition, you cannot enter a maximum passband ripple value that is greater than the stopband attenuation, nor can you enter a set of values that will lead to a filter of an order greater than 28.

Custom Filters

The custom-response option on the DESIGN screen can be used in two ways. It can be used to modify filter designs created by the method previously described, or it can be used to create filters with custom responses from scratch, by specifying a normalization value and manually entering the desired F_0 , Q , and F_n values for the necessary 2nd order and 1st order sections. To edit the response of a filter that has already been designed, press

ESC

to exit the DESIGN screen, then press

I

to re-enter the DESIGN screen. Move the cursor to "FILTER RESPONSE" and use the

Spacebar

to select "CUSTOM." You can now edit the F_0 , Q , and F_n values for the 2nd order and 1st order sections in the window at the bottom of the screen. When you customize an existing design, the normalization frequency is automatically set to the previously-specified corner/center frequency. It can, however, be edited by the user.

To design a custom filter from scratch, simply select "CUSTOM" as your response type upon first entering the DESIGN screen, then type in the appropriate F_0 , Q , and F_n values for the desired response. By default, the normalization value for custom filters is 1Hz. Once you have entered your values, you can change the normalization frequency to any desired value and FilterCAD will scale the F_0 and F_n frequencies accordingly. To change the normalization frequency, press

N

type in the new value, and press

[Enter]

By alternately graphing the resulting response and modifying the F_0 , Q , and F_n values, almost any kind of response shape can be achieved by successive approximations.

It should be understood that true custom filter design is the province of a small number of experts. If you have a

"feel" for the type of pole and Q values that produce a particular response, then FilterCAD will allow you to design by this "seat of the pants" method. If you lack such erudition, however, it is beyond the scope of the program or this manual to supply it. Nevertheless, novice designers can make productive use of FilterCAD's custom-response feature by entering design parameters from published tables. An example of this technique will be found in the following section.

STEP TWO, GRAPHING FILTER RESPONSE

After you have designed your filter, the next step is item two on the MAIN MENU, GRAPH Filter Response. You can graph the amplitude, phase, and/or group-delay characteristics of your filter, and you can plot your graph on either a linear or logarithmic scale. The graph also highlights the 3dB-down point(s) (for Butterworth filters only) and the point(s) where the calculated attenuation is achieved. An additional option on the Graph Menu is called "Reduced View." This option displays a reduced view of your graph in a window in the upper right-hand corner of the full-sized graph. This feature is useful in conjunction with the "Zoom" option.

Your graph can be displayed on the screen, output to a Hewlett-Packard 74XX or compatible plotter, or written to disk as an HPGL file or an ASCII text file for later output to a plotter or transfer to a presentation-graphics or desktop publishing program. The screen graph can also be dumped to an Epson dot-matrix or Hewlett-Packard ThinkJet or LaserJet Printer. Use the

Up-Arrow

and

Down-Arrow

keys to move through the list of graph parameters and press the

Spacebar

to step through the selections for each parameter that you wish to modify. When all of the graph parameters have been set correctly, press

[Enter]

to begin plotting the graph.

Plotting to the Screen

If you chose the screen as your output device, FilterCAD will immediately begin plotting the graph. Generating the graph is a calculation-intensive process. It is here that the speed and power of your CPU and the presence or absence of a math coprocessor will become evident. On a fast '386 system with a math coprocessor, the graph will be generated in a matter of seconds. On a PC/XT-class machine, with an 8088 processor and no math coprocessor, you can easily make and consume a cup of coffee, if not a light lunch, while waiting for the graph of a complex response to be plotted. Note, however, that the speed of calculation and plotting can be increased by reducing the number of data points to be plotted. To modify this parameter, use the "Change GRAPH Window" option, found under item 6, "Configure DISPLAY Parameters," on the Configuration Menu. The number of points can range from 50 to 500. Of course, choosing a smaller number of points will result in a coarser graph, but this may be an acceptable trade-off for quicker plotting.

The Zoom Feature — When you display the graph on the screen, you have the additional option of magnifying or "zooming in" on areas of the graph that are of particular interest. (Before using the zoom feature, it is a good idea to enable the "Reduced View" option on the graph menu. When you zoom in, the area of the zoom will be indicated by a box on the reduce view of the full-sized graph.) Note the arrow in the lower right-hand corner of the graph. This arrow can be used to select the region of the graph to zoom in on. It can also be used to pinpoint the frequency and gain values of any given point on the graph. (These values are displayed at the upper right-hand corner of the screen.) The location of the arrow is controlled by the arrow keys (the cursor control keys) on the numeric key pad. The arrow can move in either fine or coarse increments. To select coarse movement, press the

+

key. To select fine movement, press the

-

key. Move the arrow to one corner of the area that you wish to magnify, and press

[Enter]

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Next, move the arrow to the opposite corner of the area of interest. As you move the arrow, you will see a box expand to enclose the area to be magnified. If you want to relocate the box, you must press

ESC

and restart the selection process. When the box encloses the desired area, press

[Enter]

and the screen will be redrawn and a new graph will be plotted within the selected range. Note that the program actually calculates new points as appropriate for the higher precision of the magnified section.

It is possible to zoom in repeatedly to magnify progressively smaller areas of the graph. There is a limit to this process, but the available magnification is more than adequate for any practical purpose. If you want to output the magnified graph to the plotter or a disk file, you can do so. Just press

ESC

once to return to the GRAPH MENU screen, change the output device to plotter or disk, press

[Enter]

and then proceed with the plotting process as described later. To zoom out to the previous graph, press

L

(for Large). You can zoom out as many times in succession as you have zoomed in. Note, however, that for each successive zoom out the graph is recalculated and replotted. If you have done several successive zooms and you want to get back to the full-sized graph without the intermediate steps, it will be quicker to press

ESC

twice to return to the MAIN MENU, then re-enter the GRAPH screen.

Printing the Screen — If you have an Epson-FX compatible dot-matrix printer, a Hewlett-Packard ThinkJet, or a Hewlett-Packard LaserJet compatible laser printer, and

you have installed the appropriate print driver, you can dump your screen graph to your printer at any time by pressing

[Alt] P

This same feature can be used from the Device Screen (see the Implementation section) to print FilterCAD's mode diagrams. The screen-print routine will check to see whether your printer is connected and turned on, and will warn you if it is not. If your printer is connected and turned on, but off line, FilterCAD will put it on line and begin printing. Once printing begins, however, FilterCAD does no error checking, so turning off your printer or taking it off line to stop printing may cause the program to "hang up."

Plotting to a Plotter, HPGL File, or Text File

If you choose to send your graph to a plotter or to an HPGL disk file, you will first be shown the PLOTTER STATUS MENU. First, you will be asked "GENERATE CHART (Y/N)." You are not being asked here whether you want to plot a graph, but whether, when you plot to disk or plotter, you want to draw the grid or only plot the data. This may seem like an absurd choice, but it is here for a reason. If you are plotting to a plotter, you could overlay the response graphs of several different filter designs on one sheet of paper for comparison. If you drew the grid every time, you would end up with a mess. This option allows you to draw the grid on the first pass, then plot only the data on successive passes. This same process can be used, albeit with slightly more effort, when plotting to a disk file. The procedure here is to plot two (or more) separate files, the first with the grid turned on, and the remainder with the grid turned off. Then exit FilterCAD and use the DOS COPY command to concatenate the files. For example, if you wanted to concatenate three HPGL files named SOURCE1, SOURCE2, and SOURCE3 into a single file called TARGET, you would use the following syntax:

```
COPY/B SOURCE1 + SOURCE2 + SOURCE3
TARGET [Enter]
```

After you have answered the question

GENERATE CHART (Y/N)

the remainder of the PLOTTER STATUS MENU will be displayed. Here, you can select the dimensions of your graph,

the pen colors to be used, and whether to print the design parameters below the graph. When you have determined that the plotter options are set correctly, press

P

to begin plotting. If you wish to exit the PLOTTER STATUS MENU without plotting, press

ESC

You can also plot your graph as a set of data points for gain, phase and group delay plotted to disk in ASCII text format. Select

DISK/TEXT

as the output device. Then select which parameters to plot and press

[Enter]

You will then be prompted for a file name into which the data will be placed. To plot onto a disk in drive "A" type

A: [YOUR FILE] [Enter]

These points may then be imported to a spreadsheet program, for example, for data manipulation.

If your graph consists mostly of straight horizontal lines or slopes, this indicates that the frequency and amplitude ranges of the graph are probably not set appropriately for the particular filter you are graphing (e.g., a graph frequency range of 100Hz to 10,000Hz for a highpass filter with a corner frequency of 20Hz). To adjust the frequency and gain ranges of your graph, use the "Change GRAPH Window" option, found under item 6, "Configure DISPLAY Parameters," on the Configuration Menu.

IMPLEMENTING THE FILTER

The third item on the MAIN MENU, "IMPLEMENT Filter," is where we transform the numbers generated in step one into practical circuitry. There are several steps to this process.

Optimization

The first step is to optimize your filter for one of two characteristics.² You can optimize for lowest noise or lowest harmonic distortion. When you optimize for noise, the

cascaded sections are ordered in such a way as to produce the lowest output noise when the filter input is grounded. In the absence of any other, conflicting design criteria, this is the most obvious characteristic for optimization. When you optimize for harmonic distortion, the sections are cascaded so as to minimize the internal swings of the respective amplifiers, resulting in reduced harmonic distortion. *Note, however, that optimizing for harmonic distortion will result in the worst noise performance.*

The Optimization screen also allows you to select the ratio of the internal clock frequency to F_0 (50:1 or 100:1) and the clock frequency in Hz, and to turn automatic device selection on and off. It should be understood that the clock frequency ratio represents the state of a particular pin on the device, and does not necessarily correspond to the actual ratio of the clock frequency to F_0 . Thus, if you change the clock frequency to a value other than that automatically selected by FilterCAD, the frequency ratio *will not change accordingly*. Novice filter designers are advised to use the clock frequency selected by FilterCAD unless there is a compelling reason to do otherwise, and to leave automatic device selection "ON." Clock frequencies and frequency ratios are not arbitrary, but have a relationship to the corner or center frequency that depends upon the selected mode. For more information on clock frequencies, frequency ratios, and modes, consult LTC product data sheets.

When you have selected the characteristic for optimization and adjusted the other options to your satisfaction, move the cursor back to "OPTIMIZE FOR" and press

o

FilterCAD will respond by displaying the selected device and mode(s) and its rationale for selecting a particular cascade order. If you want to re-optimize for some other characteristic, press

o

again and repeat the process previously described.

Note 2: FilterCAD will not optimize custom filter designs, nor will it select the modes for such designs. This is just another indication that custom designs are the province of experienced designers.

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Implementation

When you are satisfied with the optimization, press

I

to proceed with the implementation. This won't do anything obvious except to clear the window where the optimization information is displayed, so press

D

to view the selected device, cascade order, and modes. When the Device screen is first displayed, it will show detailed specifications of the selected part. To see the mode diagrams of the 2nd and 1st order sections that implement the design, press the

Down-Arrow

key to move the cursor through the cascade-order list on the left-hand side of the screen.

You will have probably observed that, on the implementation menu, this screen is entitled "Edit DEVICE/MODEs," and you can, in fact, manually edit both the device selection and the modes of the 2nd and 1st order sections. This capability, however, is one that the novice user would be best advised to ignore. If you manually edit the device selection or the modes, you are essentially ignoring the expertise that is built into the program in favor of your own judgement. Experienced designers may choose to do this under some circumstances, but if you want to get from a specification to a working design with the least time and effort, accept the device and modes that FilterCAD selects. To complete the implementation process, press

ESC

to exit the device screen, then press

R

to calculate the resistor values. You can calculate absolute values by pressing

A

or the nearest 1% tolerance values by pressing

P

There is one more option on the implementation menu that we have not yet examined, "Edit CASCADE ORDER." This option allows you to exchange poles and zeros among and edit the cascade order of the 2nd order sections that make up your filter. This represents one of the most arcane and esoteric aspects of filter design — even the experts are sometimes at a loss to explain the benefits to be gained by tweaking these parameters. So, once again, we must recommend that the novice leave this feature alone.³

SAVING YOUR FILTER DESIGN

Item 4 on the MAIN MENU, "SAVE Current Filter Design," allows you to save your design to disk. Press

4

to save your design. By default, a new file will be saved with the name "NONAME," while a file that was previously saved and loaded will be saved under its previous name. If you want to save the file under a different name, just type it in at the cursor position. Type the file name only, eight characters or fewer; do not type an extension. All files are saved with the extension .FDF (Filter Design File).

By default, the file will be stored in the current directory (the directory that was active when FilterCAD was started). This directory will be displayed at the top of the screen. If you want to save the file to a different directory, press

Home

then type in a new path. When the file name and path are correct, press

[Enter]

to save the file. If there is already a file on the disk with the name that you have selected, FilterCAD will ask whether you want to overwrite the file. Press

Y

to overwrite the file or press

N

to save the file under a different name.

Note 3: Of course, there is no harm in the novice experimenting with the advanced features of FilterCAD, provided he or she realizes that the results of such experiments will not necessarily be useful filter designs.

LOADING A FILTER DESIGN FILE

To load a Filter Design File that you have previously saved, select

5

on the main menu. The LOAD FILE MENU screen will display a directory of all of the .FDF files in the current directory. Use the cursor keys to move the pointer to the name of the file you want to load and press

(Enter)

If there are more .FDF files than can be displayed on the screen at one time, press the

PgDn

key to see additional files. If you want to load a file from a different directory, press

P

then type in the new path. You can also enter a mask to restrict the file names which will appear on the screen. This mask can consist of any of the characters that DOS allows for file names, including the DOS wildcards "*" and "?". By default, the mask is "*", allowing all file names to be displayed. To change the mask, press

M

then type in a new mask of up to eight characters. For example, if you named your .FDF files in such a way that the first two letters of the file name represented the filter type (LP for lowpass, HP for highpass, etc.), you could change the mask to LP* to display only the lowpass filter design files.

Note: If you attempt to load an .FDF file created with an earlier version of FilterCAD, the program will issue a warning and ask you whether you want to abort loading or proceed at your own risk. Differences between .FDF files from different versions of FilterCAD are minor, and you should be able to load and use earlier .FDF files without difficulty.

Caution: When you load a filter design file, FilterCAD DOES NOT prompt you to save any design currently in memory, so when a new file is loaded, any unsaved work in memory will be lost.

CONFIGURING FILTERCAD

Item 6 on the MAIN MENU, "CONFIGURE FilterCAD," is explained in Part 1, "Getting Started."

PRINTING A REPORT

Item 7 on the MAIN MENU, "SYSTEM Status/Reports," displays a varied collection of information on your system, such as the date and time, your DOS version, the presence or absence of a math coprocessor, and the status of your printer and communications ports. It also shows the state of progress of the current design, including the total design time. (Gosh, a 6th order Butterworth lowpass in 00:05:23, only five seconds shy of the record!) The main function of this screen, however, is to print a design report. This report will include all of the information about your filter available on the design, optimization and implementation screens, except for the mode diagrams. You can also print the gain, phase and group delay of your filter design by pressing

P

Note that if you have not completed the design process by implementing the design and calculating resistor values, the "REPORT AVAILABLE" line will say "PARTIAL." A partial report, lacking modes and resistor values, can be printed, but for a complete report you must implement and calculate resistor values.

AND NOW, A WORD FROM OUR SPONSOR

The eighth item on the MAIN MENU displays Linear Technology Corporation's address and phone, fax, and telex numbers, followed by a list of our other products.

QUITTING FILTERCAD

The ninth and final item on FilterCAD's MAIN MENU, "END FilterCAD," is self-explanatory. If you haven't saved your current design before attempting to exit the program, FilterCAD will ask you if you wish to do so. Press

Y

to exit the program or press

N

to remain in FilterCAD.

PART 3—SOME PRACTICAL EXAMPLES

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Part 3— Some Practical Examples	3-1
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Now that we have examined the principal features of FilterCAD, let's walk through a few typical filter designs to get a better idea of how the program works.

A BUTTERWORTH LOWPASS EXAMPLE

First, we'll design a Butterworth lowpass filter, one of the most basic filter types. Load FilterCAD, if you haven't already done so, and press

1

to go to the design screen. Select lowpass as the design type and Butterworth as the response type. Now we have four additional parameters to enter. The passband ripple *must* be specified as 3dB; this places the cutoff frequency -3dB down with respect to the filter's DC gain. Should you desire a Butterworth response with other than 3dB passband ripple you can do so by going to the custom menu. Let's select an attenuation of 45dB, a corner frequency of 1000Hz, and a stopband frequency of 2000Hz. Press

[Enter]

after each parameter. When the last parameter is entered, FilterCAD will synthesize the response. We soon see that the result is an 8th order filter with an actual attenuation of 48.1442dB at 2000Hz. It is composed of four 2nd order lowpass sections, all with corner frequencies of 1000Hz and modest Q's. (Having the same corner frequency for all of the cascaded sections is a characteristic of Butterworth filters.) This is a good time to experiment with some of the filter's parameters to see how they affect the resulting design. Try increasing the attenuation or lowering the stopband frequency. You'll discover that any modification that results in a significantly steeper rolloff will increase the order of the filter proportionally. For instance, reducing the stopband frequency to 1500Hz changes results in a filter of order 13! If a very steep rolloff is required and some ripple in the passband is acceptable, a response type other than Butterworth would probably be preferable.

Next, we'll graph the amplitude and phase characteristics of our Butterworth lowpass filter. Press

ESC

to return to the MAIN MENU, then press

2

to go to the graph menu. We're going to output this graph to the screen, so press

[Enter]

to begin graphing immediately. In a few seconds or a few minutes, depending on the type of computer system you're using, you should see a graph very much like the one in Figure 3.1A. Amplitude (in dB's) is indicated on the left side of the graph and phase (in degrees) is indicated on the right side. (If you have your graph parameters set differently than FilterCAD's defaults, your graph may show less of the frequency and amplitude range than the figure. If you don't see a graph substantially like the one in Figure 3.1A, you may need to adjust the graph's ranges. Exit the graph screen, go to the MAIN MENU, and select 6, CONFIGURE FilterCAD. Next, select item 6, "Configure DISPLAY Parameters," followed by item 2, "Change GRAPH Window.")

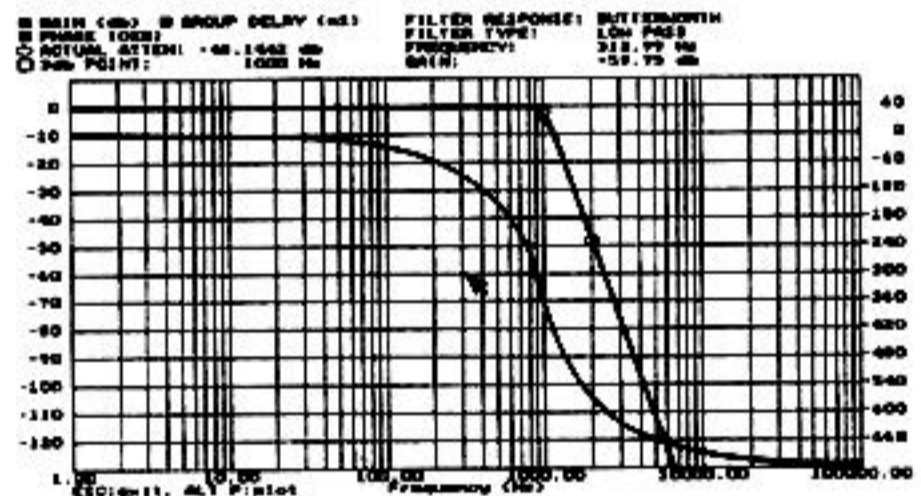


Figure 3.1A. Butterworth Lowpass Filter Response

Observe the characteristic amplitude and phase-response curves of the Butterworth response. (The amplitude curve is the one that begins at 0dB and begins to fall off sharply around 1000Hz — of course, if you have a color display you can make the amplitude and phase curves easily distinguishable by assigning them different colors.) The amplitude in the passband is extremely flat (you could magnify a small segment of the passband many times and still find no observable ripple), and the slope of the rolloff begins just before the corner frequency, reaching the 3dB down point (which, in a Butterworth response is synonymous with the corner frequency) at 1000Hz, and continues to rolloff at the same constant rate to the stopband and beyond. (In theory, the slope will continue to rolloff at this

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same rate all the way to an infinite attenuation at an infinite frequency.) The phase response begins at 0, slopes exponentially to near -360° as it approaches the corner frequency, then continues down until it asymptotes to -720° in the filter's stopband. Butterworth filters offer the most linear phase response of any type except the Bessel. Figure 3.1B shows the phase response of the Butterworth lowpass filter using a linear phase scale.

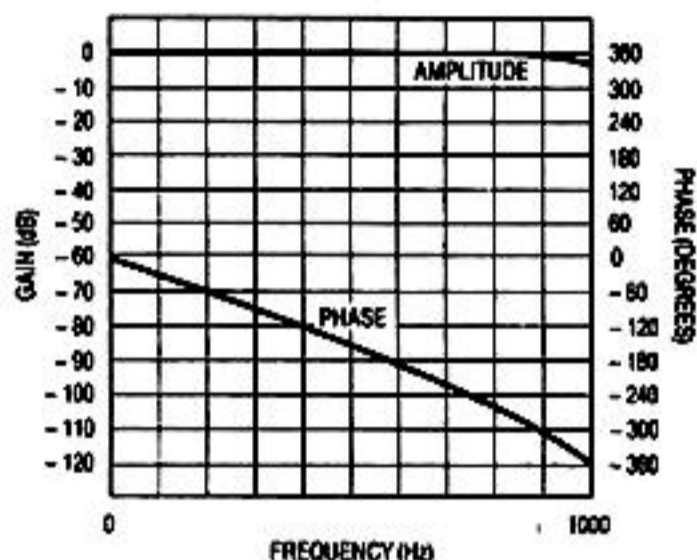


Figure 3.1B. Butterworth Lowpass Phase Response

Having graphed our filter's response, we will next go to the implementation screen to transform it into a practical design. Press

ESC

twice to exit the graph display, then press

3

to go to the implementation screen. The first step is to optimize. Lacking any other pressing need, we'll optimize for noise (the default optimization strategy). We'll use a clock frequency ratio of 50:1 and we'll leave auto device selection ON. Press

0

to execute optimization. FilterCAD selects the LTC1164 and indicates that the Q's have been intermixed for the lowest noise. Next, press

1

for implement and then

D

to display the device screen. This screen shows detailed specs of the LTC1164, and, in the window on the left-hand

side of the screen, indicates that all four of the 2nd order sections in the design will use mode 1. Press the

Down-Arrow

key and you'll see a diagram of a mode 1 network like the one in Figure 3.2 in place of the LTC1164 specs. Press the

Down-Arrow

three more times, and you'll see three more examples of the same network, differing only in their Q values. This configuration would be fine except for one thing: the LTC1164 has four 2nd order sections, but the fourth lacks an accessible summing node, and therefore cannot be configured in mode 1. You must manually change the mode of the last stage to mode 3. This illustrates the limitations of the present version of FilterCAD.

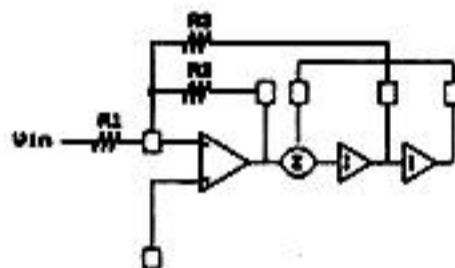


Figure 3.2. Mode 1 Network

Each mode 1 section requires three resistors, and the final mode 3 section requires four. To calculate the resistor values, press

ESC

to exit the Device screen, then press

R

On pressing

P

to select 1% tolerance resistors, FilterCAD displays the values in Table 3.1. This completes the implementation of our Butterworth lowpass example.

Table 3.1. Resistors for Butterworth Lowpass Example

STAGE	R1	R2	R3	R4
1	16.50k	15.50k	10.00k	
2	10.00k	10.00k	25.50k	
3	11.00k	11.00k	10.00k	
4	20.50k	20.50k	10.00k	20.50k

A CHEBYSHEV BANDPASS EXAMPLE

For our next example, we'll design a bandpass filter with a Chebyshev response. (We'll assume you know your way around the program reasonably well at this point, so we'll dispense with telling you specific keys to press unless we introduce a new feature.) For our Chebyshev design, we'll select a maximum passband ripple of 0.05dB, an attenuation of 50dB, and a center frequency of 5000Hz. We'll specify a pass bandwidth of 600Hz and a stop bandwidth of 3000Hz. This results in another 8th order filter, consisting of four 2nd order bandpass sections, with their corner frequencies staggered around 5000Hz and moderate Q's illustrated in Table 3.2.⁴

Table 3.2. F_o , Q, and F_n Values for 8th Order Chebyshev Bandpass

STAGE	F_o	Q	F_n
1	4857.8615	27.3474	0.0000
2	5367.2699	27.3474	INFINITE
3	4855.1190	11.3041	0.0000
4	5149.2043	11.3041	INFINITE

The Q's of the sections have been kept within reasonable limits by specifying the very low minimum passband ripple of 0.05dB. That this should be the case may not be obvious until you consider that the passband ripple consists of the product of the resonant peaks of the 2nd order sections. By keeping the passband ripple to a minimum, the Q's of the individual sections are reduced proportionally. You can verify this fact by changing the passband ripple to a higher value and observing the effect on the Q's of the 2nd order sections.

Next we'll graph the response of our design. The result appears in Figure 3.3. (We have reset the frequency range of the graph to focus on the area of interest.) Observe that the slope of the amplitude response rolls off quite steeply in the transition region and that the slopes become more gradual well into the stopband. In other words, the slope is not constant. This is a characteristic of Chebyshev filters. The characteristic passband ripple is not observable at the current scale, but we can see it by zooming in on the passband.

Note 4: It is possible to design a bandpass filter from a mixture of highpass and lowpass or highpass, lowpass, and bandpass sections, but FilterCAD will not do this. When you specify a particular filter type, all of the sections used to realize the design will be of that same type.

To zoom, first press

+

to select coarse motion, then use the arrow keys on the cursor keypad to move the arrow to one corner of the rectangle you want to zoom in on (just outside the passband), then press

(Enter)

Now move the arrow again and you'll see a box expand to enclose the area to be magnified. When the box encloses the passband, press

(Enter)

again and the new graph will be calculated and plotted. It may require two or three consecutive zooms, but eventually you'll get a closeup of the passband that shows the 0.05dB ripple quite clearly, as in Figure 3.4. (Note that in this figure, the graph style has been reset to "linear.") To return to the full-scale graph, press

L

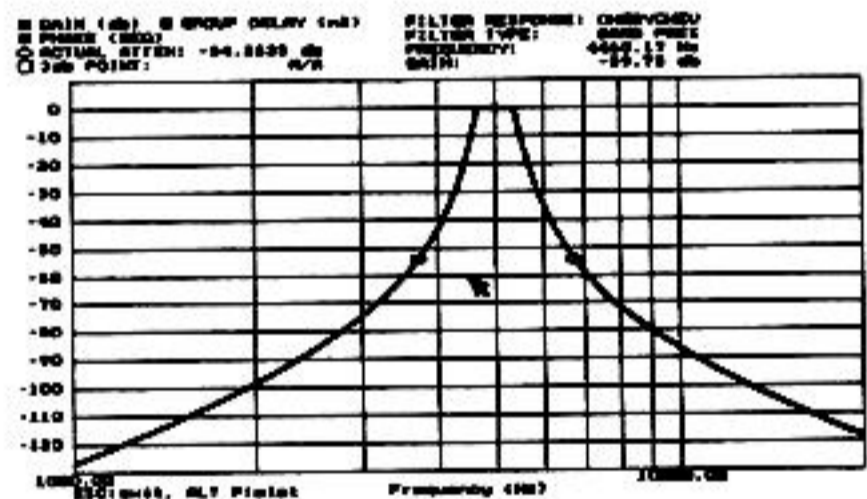


Figure 3.3. Chebyshev Bandpass Response

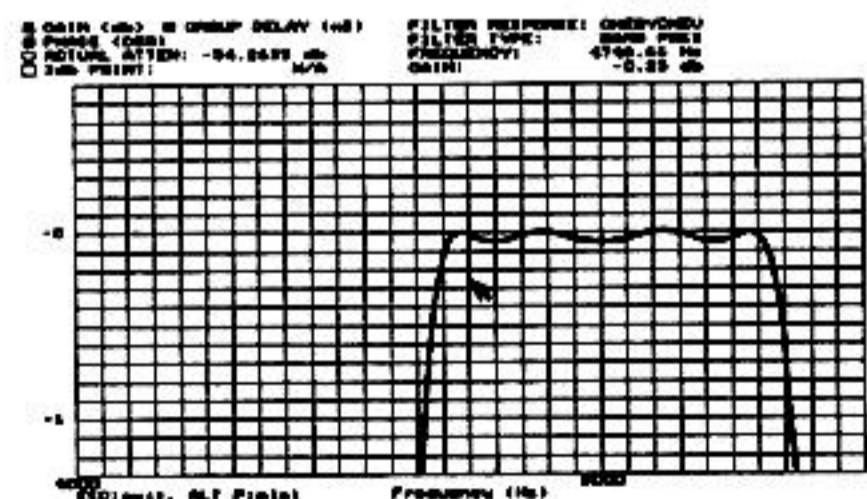


Figure 3.4. Closeup of Passband

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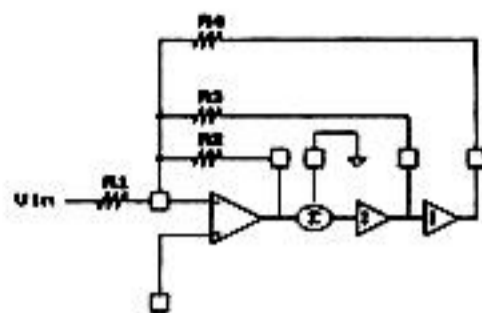


Figure 3.5A. Mode 3 Network

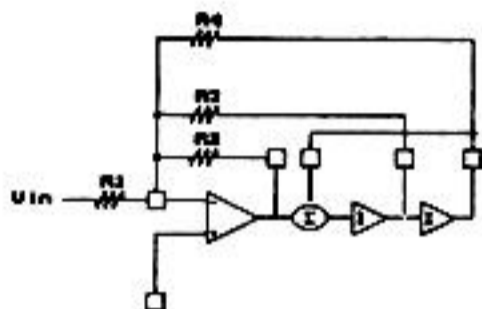


Figure 3.5B. Mode 2 Network

Now, we'll implement our design, optimizing, as before, for lowest noise. We will select clock to F_0 ratio equal to 50:1 and clock frequency equal to 250,000Hz. Once again the LTC1164 is selected and the Q's of the sections are intermixed for the lowest noise. This time mode 3 has been chosen for the first two stages (where $F_0 < F_{CLK}/50$) and mode 2 has been selected for the remaining two stages (where $F_0 > F_{CLK}/50$). The overall gain of 27.29dB has been evenly distributed among stages two through four and the gain of stage one has been set to 1 for improved dynamics. When we view the Device screen, we'll see the specs of the LTC1164 and two diagrams of the mode 3 network followed by two diagrams of the mode 2 network with different F_0 , Q, and F_n values (see Figures 3.5A and 3.5B). Calculating the 1% resistor values produces the results in Table 3.3.

Table 3.3. Resistors for Chebyshev Bandpass Example

STAGE	R1	R2	R3	R4
1	10.20k	10.00k	68.10k	10.70k
2	10.00k	12.70k	147.0k	14.70k
3	10.00k	154.0k	3.160M	1.000M
4	10.00k	12.40k	130.0k	205.0k

TWO ELLIPTIC EXAMPLES

For our next example, we will design a lowpass filter with an elliptic response. We'll specify a maximum passband ripple of 0.1dB, an attenuation of 60dB, a corner frequency

of 1000Hz, and a stopband frequency of 1300Hz. In the case of an elliptic response, we have one additional question to answer before the response is synthesized. When we have entered the other parameters, FilterCAD asks "Remove highest F_n ?" (Y/N). This question requires a bit of explanation. An elliptic filter creates notches by summing the highpass and lowpass outputs of 2nd order stages. To create a notch from the last in a series of cascaded 2nd order stages, an external op amp will be required to sum the highpass and lowpass outputs. Removing the last notch from the series eliminates the need for the external op amp, but does change the response slightly, as we will see.

Note: The last notch can be removed only from an even-order elliptic filter. If you are synthesizing an elliptic response for the first time and you are uncertain what order of response will result, answer "NO" when asked if you want to remove the last notch. If an even-order response results you can go back and remove the last notch if you wish.

For comparison, we will synthesize both responses. The F_0 , Q, and F_n values for both designs (both are 8th order) are shown in Table 3.4. Observe that the removal of the highest F_n produces slight variations in all of the other values.

Table 3.4. F_0 , Q, and F_n Values for Lowpass Elliptic Examples

STAGE	F_0	Q	F_n
Highest F_n Not Removed			
1	478.1819	0.6059	5442.3255
2	747.3747	1.3988	2032.7089
3	939.2728	3.5399	1472.2588
4	1022.0167	13.3902	1315.9606
Highest F_n Removed			
1	466.0818	0.5905	INFINITE
2	723.8783	1.3544	2153.9833
3	933.1712	3.5608	1503.2381
4	1022.0052	13.6310	1333.1141

When we graph our two elliptic examples, (Figures 3.6A and 3.6B) we see that the response of the filter without the highest F_n removed shows four notches in the stopband and a gradual slope after the last notch, whereas the filter with the highest F_n removed exhibits only three notches

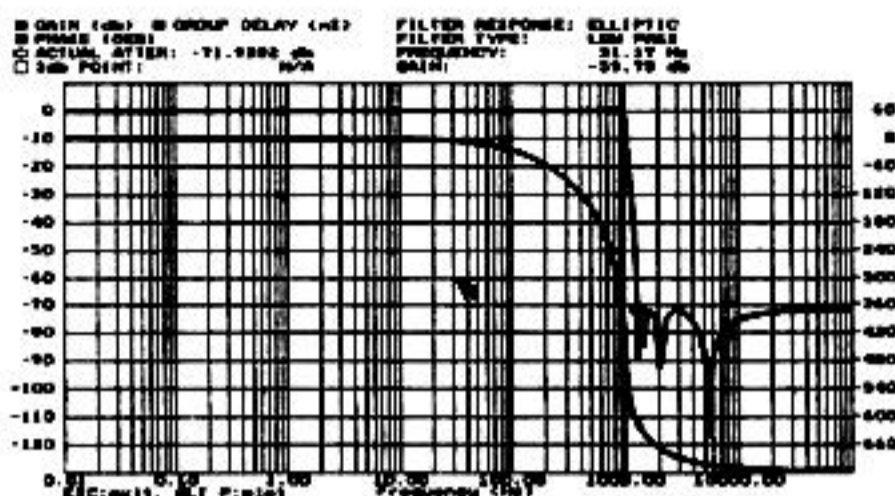


Figure 3.6A. Lowpass Elliptic, Highest F_n Not Removed

followed by a steeper slope. Both examples have the steep initial rolloff and extremely non-linear phase response in the vicinity of the corner frequency that are essential characteristics of the elliptic response. If your only goal is stopband attenuation greater than 60dB, either implementation would be satisfactory, and the version with the highest F_n removed would probably be selected due to its lower parts count.

When we optimize our two elliptic filters for noise, FilterCAD selects the LTC1164 and specifies mode 3A for all four stages. Mode 3A is the standard mode for elliptic and notch filters, as it sums the highpass and lowpass outputs of the 2nd order sections as described previously. When we go to the Device screen, we see four mode 3A diagrams, each showing the external op amp, as in Figure 3.7. In practice, this external summing amp is not needed in every case. When cascading sections, the highpass and lowpass outputs of the previous section can be summed into the inverting input of the next section, an external

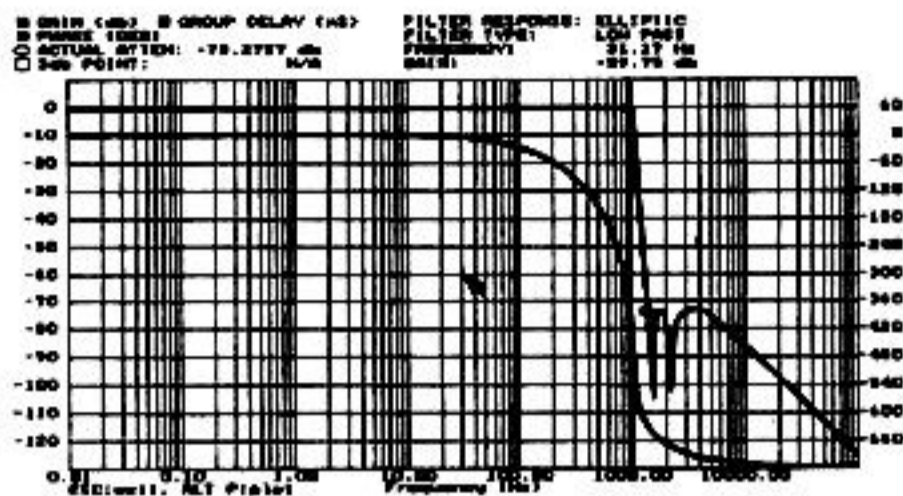


Figure 3.6B. Lowpass Elliptic, Highest F_n Removed

summing amp being required only for the last section. If the highest F_n is removed, external op amps can be dispensed with entirely.

Calculating 1% resistor values (for clock to F_0 ratio 50:1, clock frequency equals 50,000Hz) for our two elliptic variations yields the results in Table 3.5. R_H and R_L are the resistors which sum the highpass and lowpass outputs of the successive stages, and R_G is the resistor that sets the gain of the external op amp. Therefore, there is one fewer

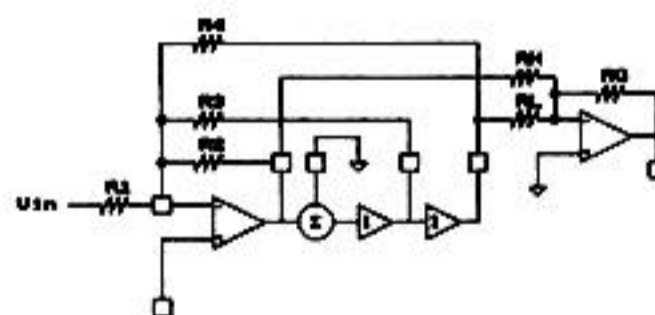


Figure 3.7. Mode 3A Network

Table 3.5. Resistor Values for Lowpass Elliptic Examples

STAGE	R1	R2	R3	R4	R _G	R _H	R _L
Highest F_n Not Removed							
1	24.90k	10.00k	17.40k	17.80k		237.0k	57.60k
2		10.50k	73.20k	10.00k		21.50k	12.70k
3		10.00k	30.90k	11.30k		21.50k	10.00k
4		19.60k	24.30k	86.60k	10.20k	294.0k	10.00k
Highest F_n Removed							
1	26.10k	10.00k	17.40k	19.10k		251.0k	58.20k
2		10.50k	75.00k	10.00k		23.20k	13.00k
3		10.00k	31.60k	11.50k		22.60k	10.00k
4		18.70k	23.20k	86.60k			

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RH/RL pair in the version with the last F_n removed, and RG is found only in the last stage of the first example. Also, R1, the resistor connected to the inverting input of the input amplifier, is used only for the first stage. The RH/RL pair takes the place of R1 in subsequent stages.

A CUSTOM EXAMPLE

For a simple example of how the custom design option works, we'll design a 6th order lowpass Bessel filter by manually entering pole and Q values. When you set the response on the Design screen to "Custom" and press

[Enter]

the usual parameter-entry stage is bypassed and you go directly to the F_o , Q, and F_n section, where you can enter any values you want. We'll use values from Table 3.6, for a filter normalized to $-3\text{dB} = 1\text{Hz}$. The published table from which these values were taken didn't mention F_n values at all, so when the author typed them in initially, he left the F_n values as he found them, as zeros. The result was not the desired lowpass filter, but its highpass mirror image. This shows the kind of trap that awaits the unwary.

Once the values have been entered, they can be re-normalized for any desired corner frequency. Just press

[Enter]

In this case we will re-normalize to 1000Hz, which simply multiplies the F_o values in the table by 1000.

Table 3.6. F_o , Q, and F_n Values for 6th Order Lowpass Bessel, Normalized for 1Hz

STAGE	F_o	Q	F_n
1	1.806	0.510	INFINITY
2	1.691	0.611	INFINITY
3	1.907	1.023	INFINITY

Looking at the graph of the resulting response (Figure 3.8), we see the characteristic Bessel response, with its droopy passband and very gradual initial rolloff. When we go to the implementation stage, the process is a little different than we are accustomed to. FilterCAD won't optimize a custom design, nor will it specify the mode(s). It will, however, select the device, (the envelope please...) the LTC1164. Now we need to go to the device screen and manually select the mode for each of the three 2nd order sections. We will select mode 3 for all sections, because the three sections each have different corner frequencies, and mode 3 provides for independent tuning of the individual sections by means of the ratio R2/R4. (We've seen what the mode 3 network looks like before, so we won't duplicate it here.) Having selected the mode, we can calculate resistor values. The results are shown in Table 3.7.

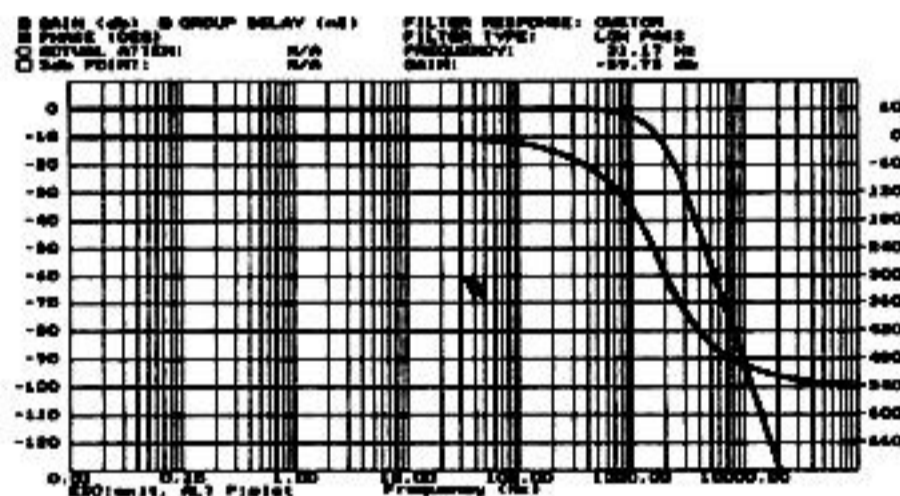


Figure 3.8. 6th Order Lowpass Bessel Response

Table 3.7. Resistors for 6th Order Bessel Lowpass Example

STAGE	R1	R2	R3	R4
1	13.00k	33.20k	10.00k	13.00k
2	10.50k	29.40k	10.00k	10.50k
3	10.00k	36.50k	17.40k	10.00k

PART 4—ADVANCED APPLICATIONS

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EDITING CASCADE ORDER

As stated earlier in this manual, optimizing performance by editing cascade order and/or swapping pole and Q values is among the most arcane and esoteric aspects of active filter design. Although certain aspects of this process are understood by experienced designers, current knowledge is not sufficiently systematic to guarantee the success of algorithmic optimization. Hence the need for manual editing. In the discussion that follows, we will consider briefly the underlying principals of optimization for minimizing noise or harmonic distortion. This will be followed by some concrete examples illustrating the effect of these principles on real-world filter designs. It should be emphasized that the fine-tuning process described here may or may not be necessary for a particular application. If you need assistance in maximizing performance of a filter using LTC parts, do not hesitate to contact our applications department for advice and counsel.

Optimizing for Noise

The key to noise optimization is the concept of band limiting. Band limiting of noise is achieved by placing the 2nd order section with the lowest Q and lowest F_0 (in the case of a lowpass filter) *last* in the cascade order. To understand why this works, we must consider the response shapes of 2nd order sections. A 2nd order section with a low Q begins rolling off before F_0 (Figure 4.1). The lower the Q, the farther into the passband the rolloff begins. 2nd order sections with high Q's, on the other hand, have reso-

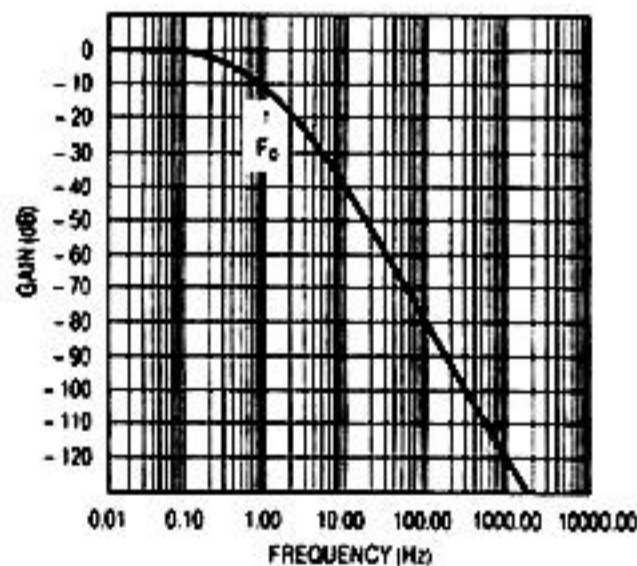


Figure 4.1. Low Q 2nd Order Lowpass Response

nance peaks centered at F_0 (Figure 4.2). The higher the Q, the higher the resulting peak. The most noise in cascaded filters is contributed by the stages with the highest Q's, the noise being greatest in the vicinity of the resonance peaks. By placing the stage with the lowest Q and the lowest F_0 last in the cascade order, we place much of the noise contributed by previous stages *outside* the passband of this final stage, resulting in a reduction of the overall noise. Also, because the final stage is the lowest in Q, it contributes relatively little noise of its own. This technique allows the realization of selective elliptic lowpass filters with acceptable noise levels.

Optimizing for Harmonic Distortion

Distortion in switched-capacitor filters can be caused by three factors. First, distortion can be produced by loading. The CMOS amplifiers that are used in LTC switched-capacitor filter devices are not suited to driving heavy loads. For best results, no node should see an impedance of less than 10k Ω , and you will observe that FilterCAD never calculates a resistor value below this limit. Further, it may be desirable, when trying to obtain optimal distortion performance, to scale up resistor values calculated by FilterCAD by a factor of two or three to minimize loading.

The second factor that affects distortion performance is the clock frequency. Each LTC switched capacitor filter device has an optimum clock frequency range. Using a clock frequency significantly above the optimal range will result in increased distortion. For information on acceptable

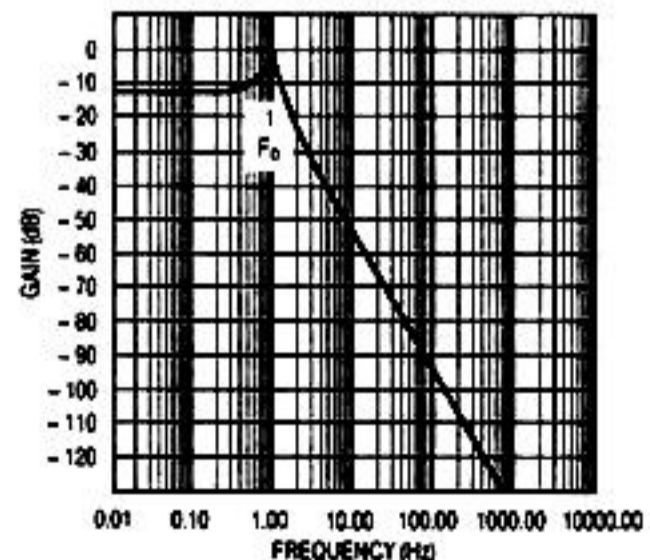


Figure 4.2. High Q 2nd Order Lowpass Response

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clock frequency ranges, consult LTC data sheets and application notes. If you do not observe these two design factors, any attempt to optimize THD performance by editing cascading order will likely be wasted.

The third factor is distortion introduced by the non-linear effects of the internal op amps when they swing close to their rails.

Both the gain and the position of the highest Q section are significant factors in this process. As previously discussed, high Q 2nd order sections ($Q > 0.707$) have a resonance peak in the vicinity of F_0 . In order to maintain an overall gain of 1 for the circuit, and to minimize distortion, it is necessary to give high Q stages a DC gain of less than 1 and proportionally increase the gain of subsequent stages. (Note that FilterCAD automatically performs dynamic optimization for designs based exclusively on mode 3A, independent of the cascading order of the 2nd order sections.) If each stage were given a gain of 1, the overall gain for the circuit would, of course, be 1. However, when a high Q section has a gain of 1 at DC, the frequencies in the vicinity of F_0 will receive an additional boost

from the resonance peak, resulting in a gain greater than 1 for those frequencies (see Figure 4.3 and the LTC1060 data sheet). Depending on the strength of the input signal, the output from the high Q stage may saturate the following input stage, driving it into its non-linear region and thereby creating distortion. Setting the gain of the high Q stage so that the peak at F_0 does not exceed 0dB results in a DC gain of less than 1 for the stage. This has the effect of significantly attenuating most of the frequencies in the passband, thereby minimizing the excursions of the input amplifier. Although this strategy reduces harmonic distortion, it can create noise problems, because the noise generated by a 2nd order stage increases with Q. (As a rule of thumb, noise can be regarded as increasing at approximately the square root of Q.) When the output from the high Q stage is amplified by subsequent stages in order to bring the overall passband gain up to 1, its noise component is amplified proportionally (Figure 4.4). Thus, as we stated previously, THD optimization is inimical to noise optimization, so the "best" cascade is a compromise between the two.

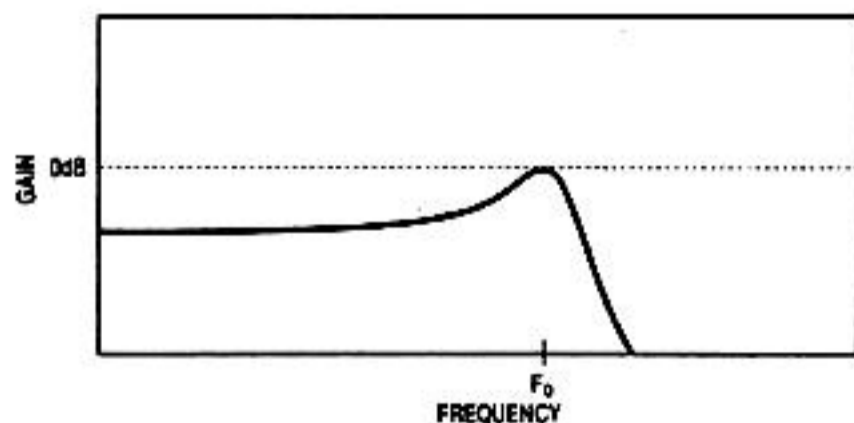
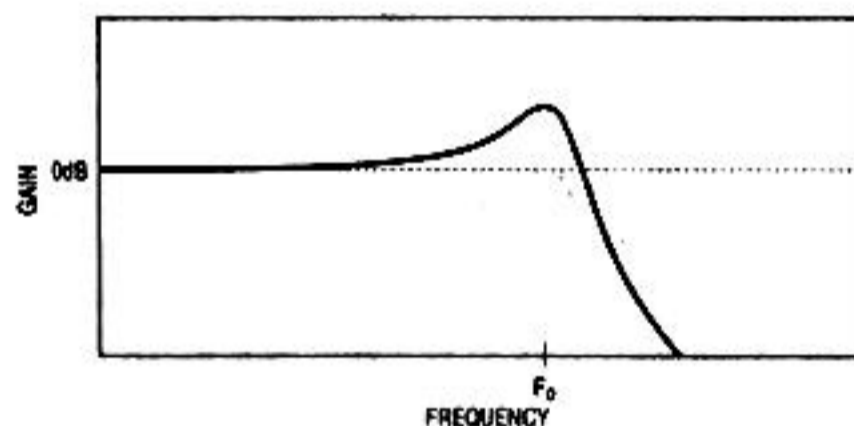
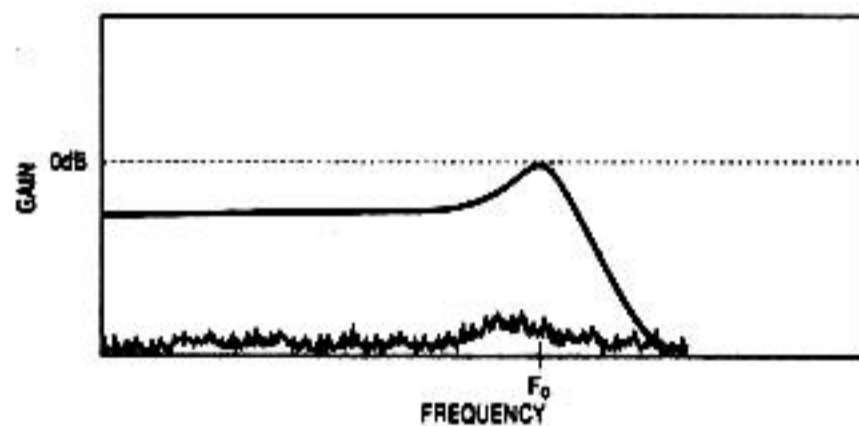
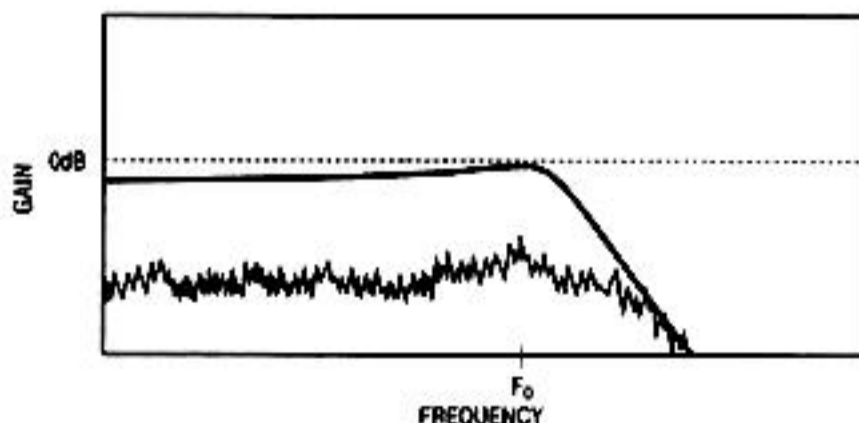


Figure 4.3. DC Gain of 1 Results in Amplitude Greater than 0dB at F_0 ; DC Gain is Reduced, Attenuating Frequencies in the Passband



HIGH Q, LOW GAIN SECTION



SUBSEQUENT SECTION WITH LOWER Q, HIGHER GAIN. NOISE FROM PREVIOUS SECTION IS BOOSTED.

Figure 4.4. Noise Generated by a High Q, Low-Gain Stage is Amplified by a Subsequent Low Q, High-Gain Stage

MORE PRACTICAL EXAMPLES

To illustrate how the sorting of cascade order can affect performance, we will examine two concrete examples. The first is an 8th order Butterworth lowpass filter, normalized to 1Hz. The maximum passband ripple is 3dB, the stopband attenuation is 48dB, the corner frequency is 1Hz, and the stopband frequency is 2Hz. Two different versions of this design were implemented, one with the cascade order sorted for decreased harmonic distortion (THD), and the other sorted for lowest noise. Table 4.1 shows the F_0 , Q , and F_n values for both versions of our example. Of the four stages, three have Q 's of less than 1, and one has a Q greater than 2.5. The two cascade orders differ only in the position of this high Q section. Observe that in the first case, the highest Q stage was placed in the second position, rather than the first, as the previous discussion indicated. This is a compromise to minimize harmonic distortion while maintaining acceptable noise performance. In the second case, the highest Q section is placed in the third position, followed immediately by the section with the lowest Q . Since this is a Butterworth filter, all of the sections have the same F_0 . Nevertheless, because the low Q section has a droopy passband (see Figure 4.2) it still has the effect of band-limiting the noise from the preceding section.

Mode 3 was selected for all stages because it produces lower harmonic distortion than mode 1. The clock-frequency ratio is 50:1, with an actual clock frequency of 400kHz giving an actual F_0 value of 8kHz. These two designs were breadboarded, using the resistor values given in Table 4.2. All of the resistor values calculated by FilterCAD were multiplied by 3.5 to minimize loading, except for the R_1 values, which were selected to set the gains for the various sections so that no node will go above 0dB (low-pass gain for mode 3 = R_4/R_1).

The harmonic distortion performance was measured, yielding the results in Figures 4.5 and 4.6. The graphs indicate total harmonic distortion as a percentage of the input voltage. Each graph shows THD performance for inputs of 1V and 2.5V_{RMS}. The difference between the two designs with a 1V_{RMS} input is negligible, but with a 2.5V input, a clear improvement in harmonic distortion is visible in Figure 4.5. In both examples, the distortion takes a

Table 4.1. F_0 , Q , and F_n Values for 8th Order Butterworth Lowpass

STAGE	F_0	Q	F_n
Sorted for Reduced Harmonic Distortion			
1	1.0000	0.6013	INFINITE
2	1.0000	2.5629	INFINITE
3	1.0000	0.9000	INFINITE
4	1.0000	0.5098	INFINITE
Sorted for Low Noise			
1	1.0000	0.6013	INFINITE
2	1.0000	0.9000	INFINITE
3	1.0000	2.5629	INFINITE
4	1.0000	0.5098	INFINITE

Table 4.2. Resistor Values for 8th Order Butterworth Lowpass

STAGE	R_1	R_2	R_3	R_4	DC GAIN
Optimized for Reduced Harmonic Distortion					
1	61.90k	60.90k	35.00k	60.90k	0.96
2	57.60k	35.00k	77.35k	35.00k	0.61
3	43.20k	42.35k	35.00k	42.35k	0.96
4	39.20k	71.75k	35.00k	71.75k	1.83
(Total)					1.05
Optimized for Low Noise					
1	60.20k	60.90k	35.00k	60.90k	1.01
2	41.60k	42.35k	35.00k	42.35k	1.00
3	56.20k	35.00k	77.35k	35.00k	0.60
4	43.20k	71.75k	35.00k	71.75k	1.66
(Total)					1.05

significant dip as we approach the corner frequency. This is somewhat deceptive, however, since in this region the third and higher harmonics begin to be attenuated by the filter. While giving better harmonic distortion performance, Figure 4.5 has a wideband noise spec of 90 μ V_{RMS}, whereas Figure 4.6 yielded a wideband noise spec of 80 μ V_{RMS}.

Our second example is a 6th order elliptic lowpass filter, again normalized to 1Hz and realized in two versions, one optimized for noise, and the other optimized for harmonic distortion. This example has a maximum passband ripple of 1dB, a stopband attenuation of 50dB, a corner frequency of 1Hz, and a stopband frequency of 1.20Hz. The

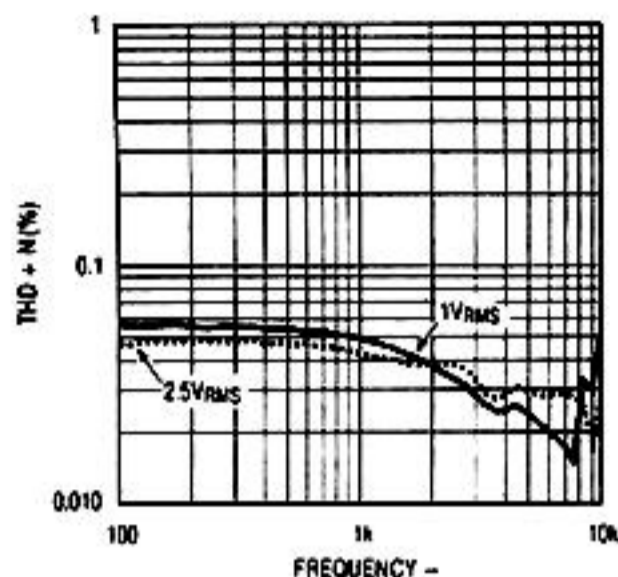


Figure 4.5. THD Performance, 8th Order Butterworth Sorted for Reduced THD

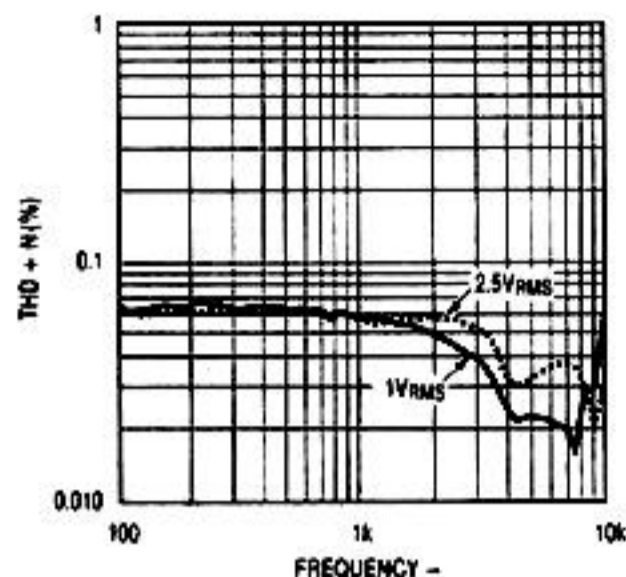
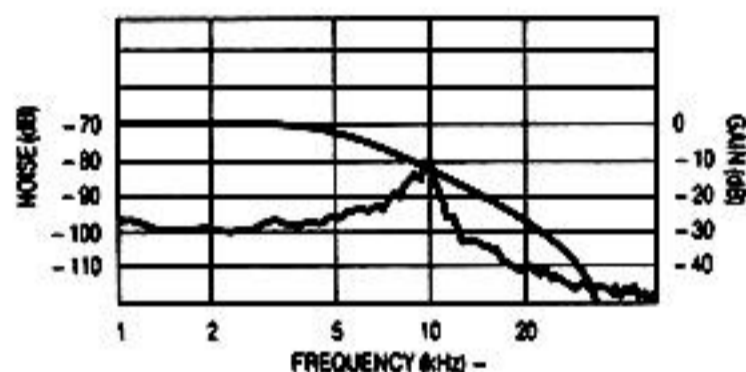
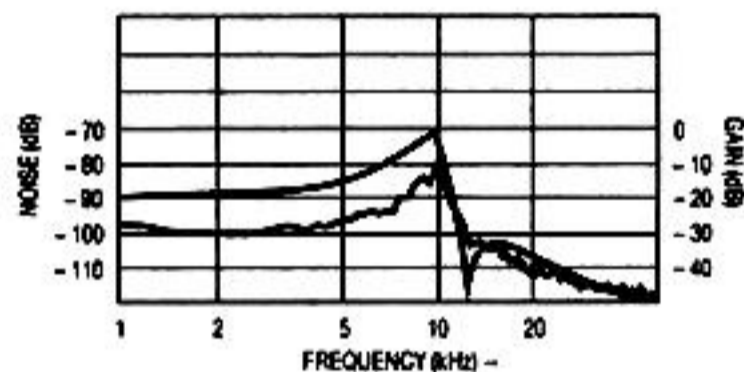


Figure 4.6. THD Performance, 8th Order Butterworth Sorted for Reduced Noise



GAIN AND NOISE OF SECOND ORDER ELLIPTIC SECTION BANDLIMITING NOISE FROM PREVIOUS SECTION. $Q = 0.79$, $F_0 = 4.8\text{kHz}$, $F_n = 38\text{kHz}$.



GAIN AND NOISE OF SECOND ORDER ELLIPTIC SECTION BANDLIMITING NOISE FROM PREVIOUS SECTION. $Q = 15$, $F_0 = 10\text{kHz}$, $F_n = 12.2\text{kHz}$.

Figure 4.7. Using Cascade-Order to Band-Limit Noise

clock to filter cutoff frequency ratio is 100:1. The cascade orders for the two sections are given in Table 4.3. The case of an elliptic filter is more complex than the Butterworth in that the 2nd order responses have F_n values (notches or 0's) as well as F_0 's and Q 's. The ratio of F_n to F_0 in a particular section affects the height of the resonance peaks resulting from high Q 's. The closer F_n is to F_0 , the lower the peak.

Table 4.3. F_0 , Q , and F_n Values for 6th Order Elliptic Lowpass

STAGE	F_0	Q	F_n
Sorted for Reduced Harmonic Distortion			
1	0.9989	15.0154	1.2227
2	0.8454	3.0947	1.4953
3	0.4618	0.7977	3.5990
Sorted for Low Noise			
1	0.8454	3.0947	1.4953
2	0.9989	15.0154	1.2227
3	0.4618	0.7977	3.5990

In the first instance, the section with the highest F_0 and the highest Q is paired with the lowest F_n , and placed first in the cascade order. The second-highest Q is paired with the second-lowest F_n , and so on. This pairing minimizes the difference between the highest peak and the lowest gain in each second order section. Referring to Table 4.4, which gives the resistor values and lowpass gains for the stages, we see that the first stage has a very low gain of 0.067, and that most of the gain is provided by stage three, which has the lowest Q . Thus, the input swings of the individual stages are minimized, input-induced distortion is reduced, and an overall gain of 1 for the circuit is obtained. (In the case of mode 3A sections, lowpass gain for the first section is determined by R_4/R_1 , and lowpass gain for subsequent stages is determined by R_4 divided by R_L of the previous stage. The final gain stage is provided by the external op amp, and is determined by R_G/R_L . Highpass gain is not taken into account here.)

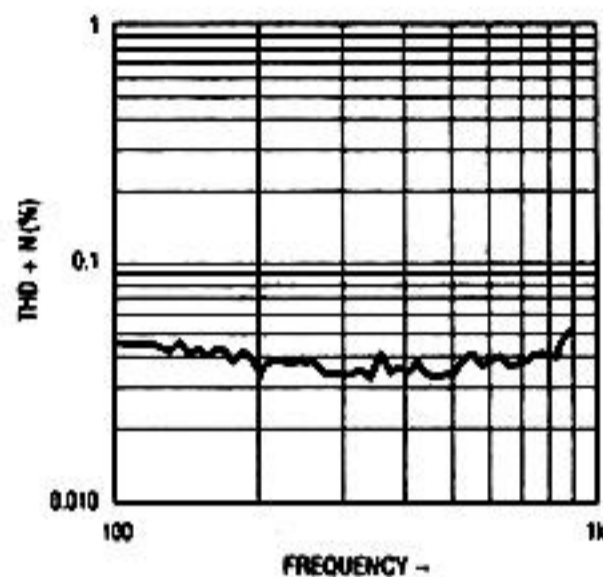


Figure 4.8. THD Performance, 6th Order Elliptic Sorted for Reduced THD

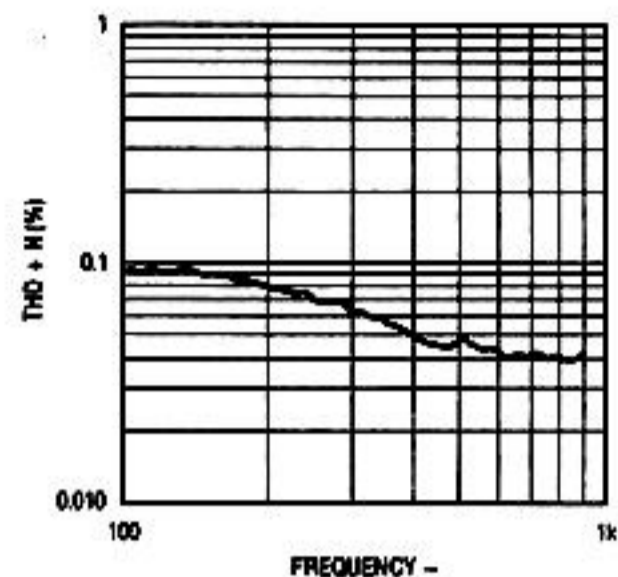


Figure 4.9. THD Performance, 6th Order Elliptic Sorted for Reduced Noise

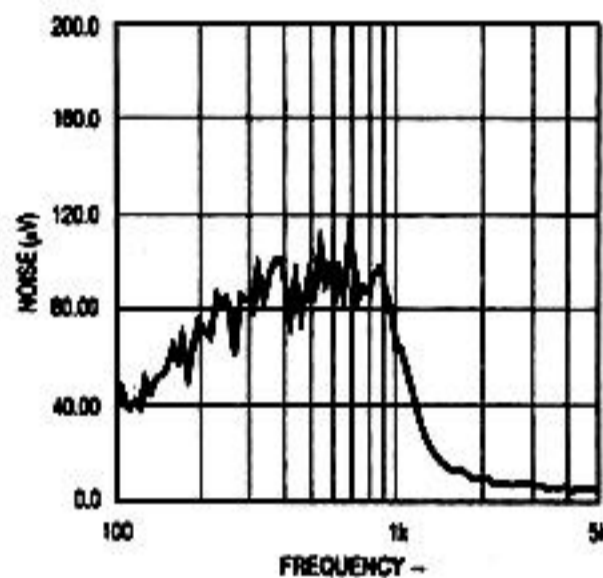


Figure 4.10. Noise Performance, 6th Order Elliptic Sorted for Reduced THD

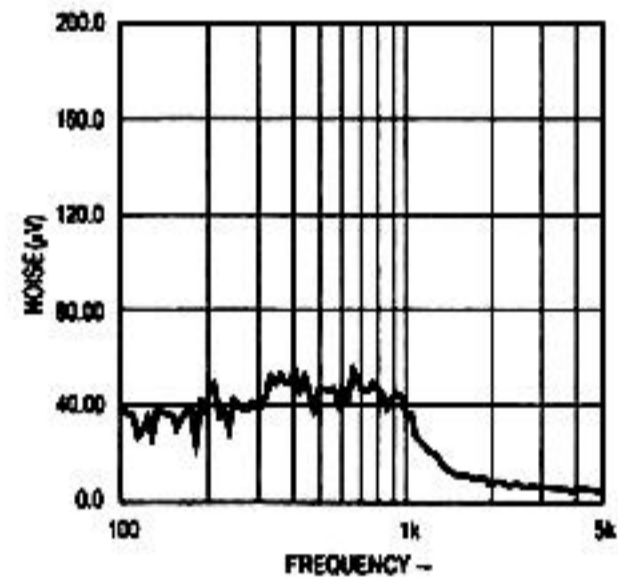


Figure 4.11. Noise Performance, 6th Order Elliptic Sorted for Reduced Noise

In the second example, 2nd order stages have been sorted for reduced noise. In this case, the stage with the highest Q and F_0 is placed in the middle of the cascade order and is followed immediately by the stage with the lowest Q and F_0 . Most of the gain is provided by stage three, which would tend to boost the noise generated by the previous stage, but the greater-than-2:1 ratio between the F_0 's of the two sections causes much of the noise generated by stage two to fall outside of stage three's passband (See Figure 4.7). This produces the band-limiting effect described previously, and improves the overall noise performance of the circuit significantly. Figures 4.8 through 4.11 detail noise and THD performance of the two 6th order elliptic examples.

NOTCHES...THE FINAL FRONTIER

Notch filters, especially those with high Q 's and/or high attenuations, are the most difficult to implement with universal switched-capacitor filter devices. You may design a notch filter with FilterCAD, with specifications that purport to yield a stopband attenuation of greater than 60dB, and find that in practice an attenuation of 40dB or less is the result. This is primarily due to the sampled data nature of the universal filter blocks; signals of equal amplitude and opposite phase do not ideally cancel when summed together as they would do in a purely analog system. Notches of up to 60dB *can* be obtained, but to do so requires techniques not covered by this version of FilterCAD. Some of these techniques will be examined here.

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Table 4.4. Resistor Values for 8th Order Lowpass Elliptic (100:1, F_{CLK} to F_c)

STAGE	R1	R2	R3	R4	RG	RH	RL	LOWPASS GAIN
Sorted for Low THD								
1	150.0k	10.00k	150.0k	10.00k		15.00k	10.00k	0.067
2		11.80k	43.20k	16.50k		22.60k	10.00k	1.650
3		16.90k	28.70k	78.70k	11.50k	130.0k	10.00k	7.870
External Op Amp								1.150
(Total)								1.000
Sorted for Low Noise								
1	43.20k	10.00k	36.50k	14.00k		110.0k	48.70k	0.324
2		10.00k	150.0k	10.00k		15.00k	10.00k	0.205
3		28.00k	48.70k	130.0k	11.50k	130.0k	10.00k	13.00
External Op Amp								1.150
(Total)								0.993

Table 4.5. F_o , Q, and F_n Values for 40kHz, 60dB Notch

STAGE	F_o	Q	F_n
1	35735.6793	3.3144	39618.8585
2	44773.1799	3.3144	40388.8469
3	35242.9618	17.2015	39085.8415
4	45399.1358	17.2105	40935.5393

Table 4.6. F_o , Q, and F_n Values for 40kHz, 60dB Notch

STAGE	F_o (kHz)	Q	F_n (kHz)	MODE
1	40.000	10.00	40.000	1
2	43.920	11.00	40.000	2
3	40.000	10.00	40.000	1
4	35.920	8.41	40.000	3

We will start by using FilterCAD to enter the parameters for an elliptic notch response. We'll specify a maximum passband ripple of 0.1dB, an attenuation of 60dB, a center frequency of 40kHz, a stop bandwidth of 2kHz, and a pass bandwidth of 12kHz. Given these parameters, FilterCAD synthesizes the response shown in Table 4.5. This 8th order filter claims an actual stopband attenuation of greater than 80dB, a level of performance that would be exceedingly difficult to achieve in the real world. A working filter with an attenuation of 60dB can be achieved, but only by deviating significantly from the advice provided by FilterCAD.

Switched-capacitor filter devices give the best performance when certain operating parameters are kept within particular ranges. Those conditions which produce the best results for a particular parameter are called its "figure of merit." For example, in the case of the LTC1064, the best specs for clock to center frequency ratio (F_{CLK}/F_o) accuracy are published for a clock frequency of 1MHz and a Q of 10. As we depart from this "figure of merit" (as we must do to produce the 40kHz notch in our example), per-

formance will gradually deteriorate. One of the problems that we will encounter is "Q-enhancement." That is, the Q's of the stages will appear slightly greater than those set by resistors. (Note that Q-enhancement is mostly a problem in modes 3 and 3A and is *not* limited to notches but occurs in LP, BP and HP filters as well.) This results in peaking above and below the notch. Q-enhancement can be compensated for by placing small capacitors (3pF–30pF) in parallel with R4 (mode 2 or 3). With this modification, Q-enhancement can be compensated for in notch filters with center frequencies as high as 90kHz. The values suggested here are compromise values for a wide-range clock-tunable notch. If you want to produce a fixed-frequency notch, you can use larger caps at higher frequencies. At least in the case of the LTC1064, Q-enhancement is unlikely to be a problem below 20kHz. Adding capacitors at lower frequencies will have the effect of widening the notch.

As mentioned previously, the other problem in implementing notch filters is inadequate attenuation. For low frequency notches, stopband attenuation may be increased

by boosting the clock to notch frequency up to 250:1. Attenuation may also be improved by adding external capacitors, this time in parallel with R2 (modes 1, 2, and 3A). Capacitors of 10pF–30pF in this position can increase stopband attenuation by 5dB–10dB. Of course, this capacitor/resistor combination constitutes a passive 1st order lowpass stage with a corner frequency at $1/(2\pi RC)$. In the case of the values indicated above, the corner frequency will appear so far out in the passband that it is unlikely to be significant. However, if the notch is needed at a frequency below 20kHz, the capacitor value will need to be increased and the corner frequency of the 1st order stage will be lowered proportionally. For a capacitor of 100pF and an R2 of 10k, the corner frequency will be 159kHz, a value that is still unlikely to cause problems in most applications. For a capacitor of 500pF (a value that might prove necessary for a deep notch at a low center frequency) and an R2 of 20k, the corner frequency drops down to 15.9kHz. If maximum stopband attenuation is more important than a wide passband, such a solution may prove acceptable. Adding resistors in parallel with R2

produces one additional problem: It increases the Q that we just controlled with the capacitors across R4. Resistor values must be adjusted to bring the Q down again.

Table 4.6 contains the parameters for a *real* notch filter which actually meets our 60dB attenuation spec using the techniques previously outlined. This is essentially the clock-tunable 8th order notch filter described in the LTC1064 data sheet. Note the mixture of modes used. This is a solution that FilterCAD is incapable of proposing.

It should be apparent that the methods for notch filters described here are primarily empirical at this point, and that the account given here is far from comprehensive. We have not even touched on optimizing these filters for noise or distortion, for instance. No simple rules can be given for this process. Such optimization is possible, but must be addressed on a case-by-case basis. If you need to implement a high-performance notch filter and the tips above prove inadequate, please call the LTC applications department for additional assistance.

PART 5—APPENDICES

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APPENDIX 1

The FilterCAD Device-Parameter Editor

The FilterCAD Device-Parameter Editor (FDPF.EXE) allows you to modify the FilterCAD Device-Parameter File (FCAD.DPF). This file contains the data about LTC switched-capacitor filter devices which FilterCAD uses in making device selections in its implementation phase. The Device-Parameter Editor is a menu-driven program that has a similar command structure to FilterCAD. Its main menu includes the following entries:

1. ADD New Device
2. DELETE Device
3. EDIT Existing Device
4. SAVE Device Parameter File
5. LOAD Device Parameter File
6. CHANGE Path to Device Parameter File

9. END Device Parameter Editor

The principle reason for editing the Device-Parameter File is to add data for new LTC devices that were released after this revision of FilterCAD. To enter data for a new device, press

1

You will see a blank form with fields for the necessary parameters. Use the arrow keys to move through the fields and type in the appropriate values from the LTC data sheet. Press

[Enter]

to accept the data in each field, then press

ESC

when you have finished entering the data. Don't forget to SAVE the new .DPF file. The program will inform you that the FCAD.DPF already exists and ask you whether you want to overwrite it. Press

Y

to save your file.

Another possible reason for using the Device-Parameter Editor is to delete some devices from the Device-Parameter File so that FilterCAD could only select devices that you have on hand. To delete a device, press

2

When it shows you a device name on the screen, press

Y

to delete the device from the file or press

N

to cycle through the list of devices until it displays the one that you wish to delete.

You can also use the Device-Parameter Editor to edit the data for a device supported by this version of FilterCAD in the event that the specifications for that device are revised. To edit a device already in the Device-Parameter File, press

3

You will see a form, like the one described previously for adding new devices, except the fields will contain data. Use the

PgDn

and

PgUp

keys to page through the devices to find the one you wish to edit, move the cursor to the fields that you want to modify and type in the new data. You must press

[Enter]

to accept the new value in each field. Press

ESC

when you have finished editing.

The remainder of the options on the Device-Parameter File Editor's main menu are self explanatory.

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APPENDIX 2

Bibliography

For more information on the theory of filter design, consult one of the works listed below.

1. Daryanani, Gobind, "Principles of Active Network Synthesis and Design." New York: John Wiley and Sons, 1976.
2. Ghausi, M.S., and K.R. Laker, "Modern Filter Design, Active RC and Switched Capacitor." Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1981.
3. Lancaster, Don, "The Active Filter Cookbook." Indianapolis, Indiana: Howard W. Sams & Co., Inc., 1975.
4. Williams, Arthur B., "Electronic Filter Design Handbook." New York: McGraw-Hill, Inc., 1981.