

Tube-Based Crossovers

Just behind tube phono preamps and tube headphone amplifiers, the largest number of circuit requests I receive is for tube-based crossovers. Using tubes rather than ICs in a crossover requires no justification for those who already have a tube-based system. But for those not so lucky, or for those solid-state besotted, they will be pleased to learn that the tube does not sacrifice too much measured performance compared to the IC in this application; however, they will be saddened by the fourfold increase in cost. So is a tube crossover worth the cost and effort? One friend tells me that the single biggest improvement in his system resulted from replacing his expensive solid-state active crossover with a tube-based one.

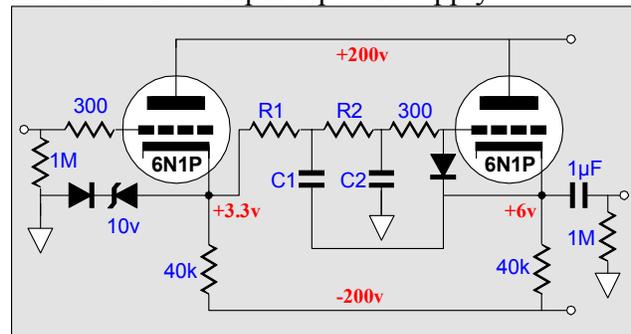
Fortunately, the vacuum tube is better suited to the task of actively buffering filter components than it is to other tasks such as amplifying the frail phono cartridge's output or driving the headphone's punishingly low impedance. However, taking advantage of the vacuum tube's attributes requires a little extra thought when designing a tube-based crossover to maximize the performance and to protect the tube from possible damage.

Bipolar Power Supplies

The easiest tube topology to implement is based on cathode followers and bi-polar power supplies. The cathode followers both isolate the filter sections and provide the means of interjecting positive feedback back into the filter. The positive feedback aspect is seldom considered, but it is vital to creating an active filter. You see in the absence of the reactive pairing of inductor and capacitor, there is only lost gain and gain is necessary to compensate for the otherwise sagging output of a purely capacitive and resistive network. The unity gain output of a cathode follower bootstraps signal going into the filter, which allows for the elimination of the inductor. (And as was covered in the previous article, inductors are a nuisance.)

The bipolar power supply allows us to keep the heater power supply referenced to ground and it allows for DC coupling at the input, two real benefits. Yet many tube aficionados won't touch a bipolar power supply. True it is harder to make a bipolar power supply with tube rectifiers and off-the-shelf power transformers. But making a bipolar power supply with solid-state rectifiers and center-tapped off-the-shelf power transformers is a breeze.

Still, the advantages that derive from using the bipolar power supply are worth looking into. For example, the goal of not using the signal ground for any purpose other than signal processing is much more easily done and often power supply noises can be made to cancel with a bipolar power supply. The circuit below shows a tube filter that uses a bipolar power supply.

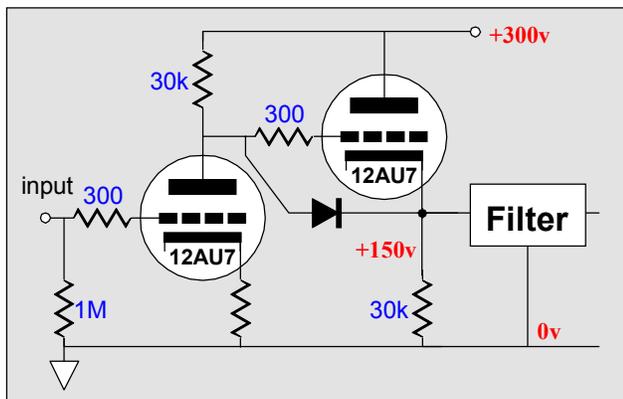


Bipolar power supply based crossover

This is a 2nd order lowpass filter that can be made to realize a Bessel, Butterworth, Gaussian, or Linkwitz-Riley alignment depending on the relative values of resistors R1, R2 and capacitors C1, C2. The 6N1P is a Russian tube that has earned the respect of many tube fans. It has a μ of 34 and an r_p of 9750 ohms at 200 volts and 5 mA. It is similar to the 6DJ8, but *not at all directly interchangeable with it*. This circuit protects its tubes by including three diodes. The first two, the zener-diode pair, only conduct when the cathode falls below about 10.7 volts. The last diode is normally reverse biased and only conducts when the grid is over .7 volts more positive than the cathode (something that should never happen). The only time any of these diodes should conduct is when power is first applied and the tube is still cold.

Single Polarity Power Supplies

We still need to use cathode followers to isolate the filter elements and to provide positive feedback. We cannot just ground referenced DC couple the input to the cathode follower, as the cathode follower's distortion increases with a decrease cathode load resistance. This means the cathode follower must find a DC bias voltage so that a large valued cathode resistor can be used. Two approaches present themselves: we can add a grounded-cathode amplifier to the input and then DC couple to its output or we can use a coupling capacitor and a resistor voltage divider network to establish the required DC bias voltage.

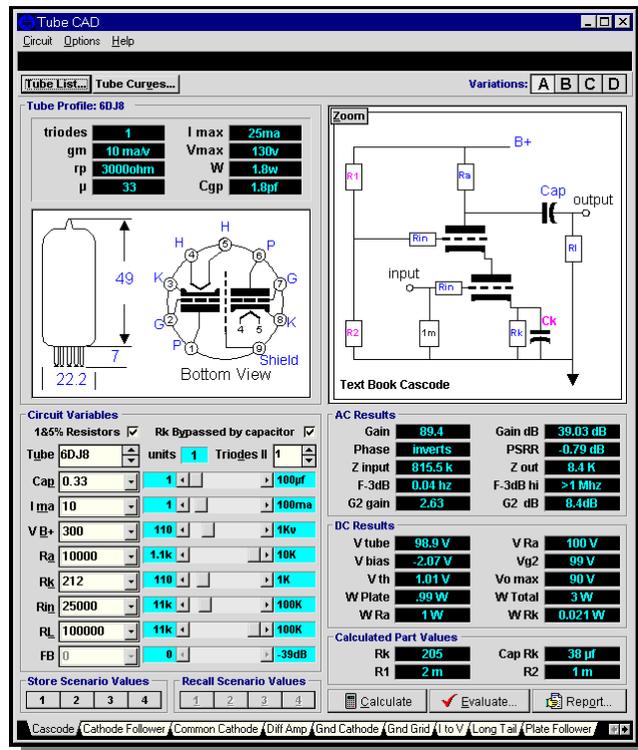


DC coupled gain producing input stage

The circuit above has the advantage, or disadvantage, depending on your perspective, of providing some gain. The advantage of having gain is that it offers more flexibility. Passive attenuator boxes can be used with a active filter that provides gain, as gain overrides the insertion losses of the filter. And since different amplifiers differ in gain and since high-frequency drivers are usually much more efficient than low-frequency drivers, the active filter with gain allows us to use potentiometers to bring each driver up or down to a baseline.

The disadvantage to gain is that the gain is not free. We had to pay for it with increased distortion and noise. Obtaining a cleaner gain requires more circuitry and a possibly a cleaner power supply. The simple cathode follower circuit, on the other hand, is clean and quiet.

Tube CAD

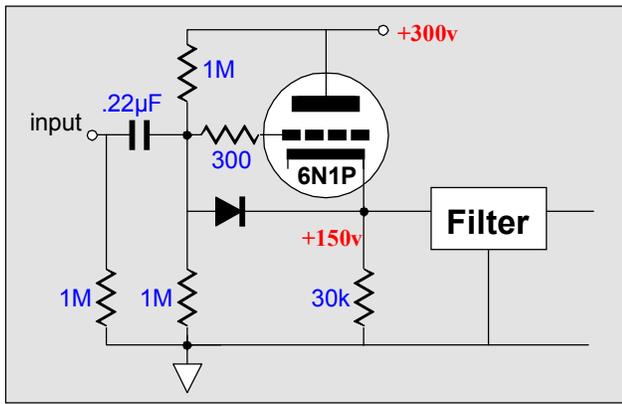


Tube CAD does the hard math for you. This program covers 13 types of tube circuits, each one divided into four variations: 52 circuits in all. Tube CAD calculates the noteworthy results, such as gain, phase, output impedance, low frequency cutoff, PSRR, bias voltage, plate and load resistor heat dissipations. Which tube gives the most gain? Tube CAD's scenario comparison feature shows which tube wins.

Windows 95/98/Me/NT/2000

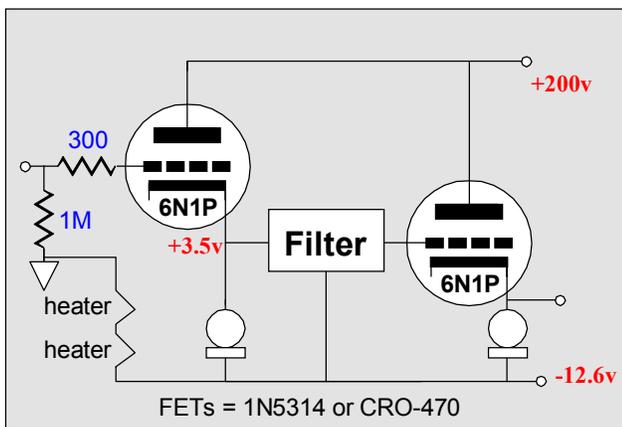
For more information, please visit our Web site :

www.glass-ware.com

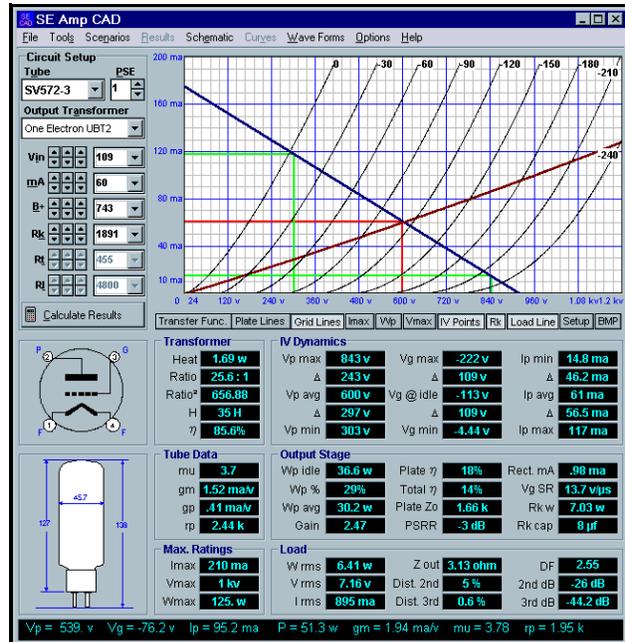


The circuit above uses the coupling capacitor and two resistor voltage divider to DC bias correctly the cathode follower. The gain is close to unity and output impedance is low enough not interact too greatly with the filter components. The diode serves to protect the 6N1P at turn on. The coupling capacitor can become part of the crossover. For example, bi-amped satellite loudspeaker might require a 100 Hz crossover point between it and the subwoofer. In this case the .22µF capacitor must be replaced with a 3183pF capacitor. (The two 1M resistors are in parallel, thus the terminating resistance for this capacitor is 500k.)

A third possibility is to make a hybrid crossover, tubes on top and FETs on the bottom. The circuit below uses a DC power supply to power both the heater string and to load the cathode followers. The constant current source can be the two lead FET current sources such as the 1N5314 or CRO-470. (Many tube fanciers will tolerate a solid-state device, but only if it has two leads, strange but true.)



SE Amp CAD



Successful design and analysis of a single-ended amplifier output stage requires an accurate model of the tube's plate curves. SE Amp CAD is a tube audio design program that has a library of 30 tubes and over 100 output transformers and SE Amp CAD knows how these tubes really curve in a singled-ended amplifier.

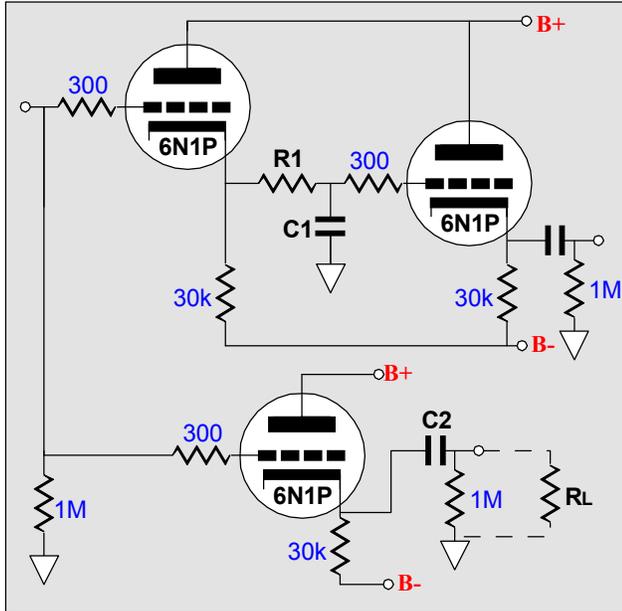
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For more information, please visit:

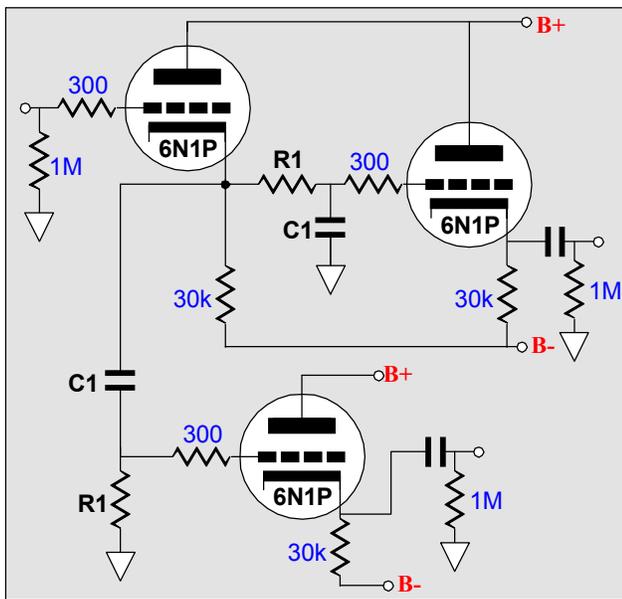
www.glass-ware.com

1st Order Filters

Simplicity itself: a resistor and a capacitor in between two cathode followers. We can eliminate some the components in the signal path but at the cost of eliminating some its universality. The circuit below makes the point.

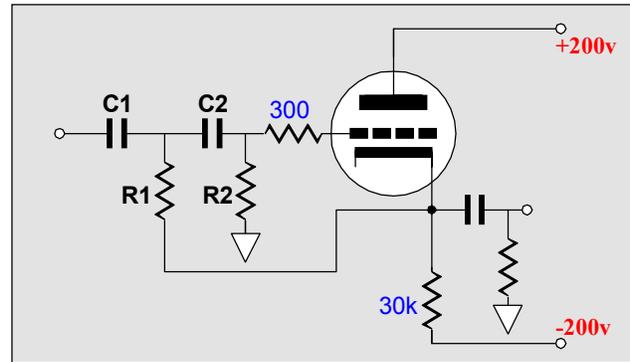


The low pass filter is safely tucked inside the two cathode followers and the highpass filter is buffered from the output impedance of the signal source; but its termination is can change with a different power amplifier. Consequently, a better choice might be to enclose the high pass filter within the confines of the two cathode followers.



2nd Order Filters

The 2nd and higher order filters rely on the cathode follower to provide positive feedback at some frequencies to define the desired crossover shape. In the highpass filter below, resistor R1 provides the positive feedback path back into the circuit.



2nd Order highpass filter

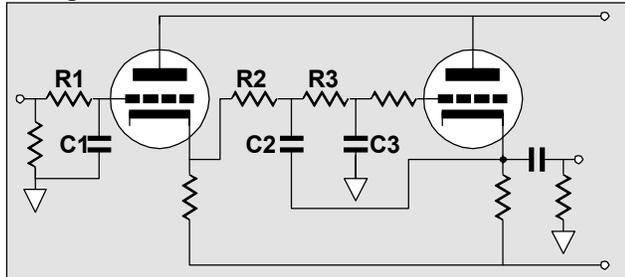
The deviation between resistors R1 and R2 and the “nominal” resistor values defines the Q of the filter. The nominal value is the textbook ($R = 1/(2\pi fC)$) value. For example, given a crossover frequency of 1 kHz and a capacitor C1 value of $.159\mu F$, the nominal resistor value is 1k. In a Butterworth filter, R1’s value would be 707 ohms; R2, 1414 ohms. The Butterworth filter uses $1/\sqrt{2}$ and $\sqrt{2}$ to achieve its alignment. Thus the ratio between R1 and R2 is 2.

The Bessel filter uses a more complicated ratio: $R1 = 3/4 \times R2$. R2 is twice the nominal value and R1 is 75% of R2’s value. At the core of these relationships is $\sqrt{3}$. For example, $(\sqrt{3} / 2)^2 = 3/4$. Fortunately, once one set of resistor and capacitor values have been determined, setting a different crossover frequency only requires scaling either (but not both) the resistor or the capacitor values up or down.

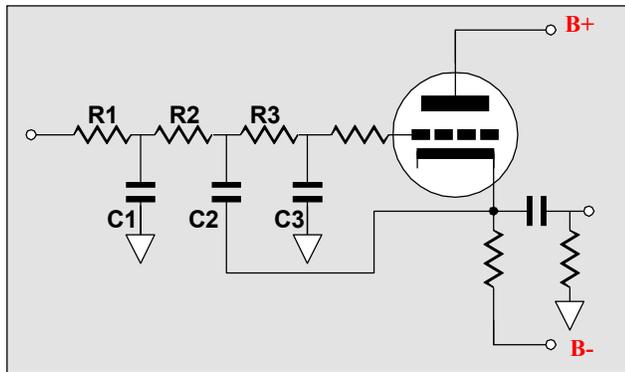
(Q is the inverse of the damping factor of a filter. Thus a Q of .5 equals a damping of factor of 2. Thus the higher the Q, the less damped the filter is and the more likely it is to ring or peak. The lower the Q, the more likely the output will droop at the crossover frequency. Expect to see both Q and “damping” used in the literature.)

3rd Order Filters

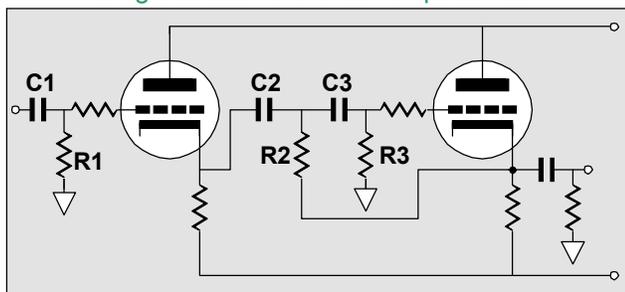
Two ways of making a 3rd order filter exists. The first is to have a 2nd order filter cascade with 1st order filter. The Q of the 2nd order filter must be made to compensate for the un-adjustable 1st order filter. The second approach is to place all the RC sections in series.



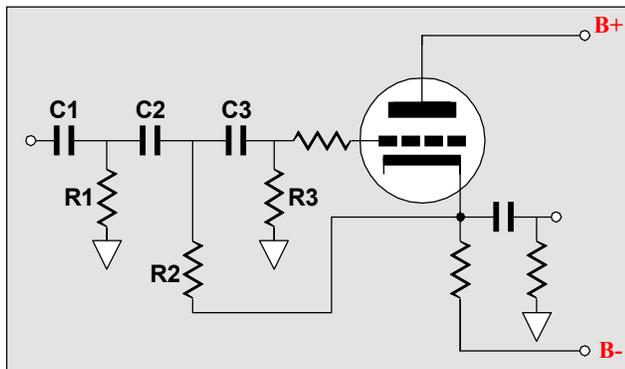
Two section 3rd order lowpass filter



Single section 3rd order lowpass filter

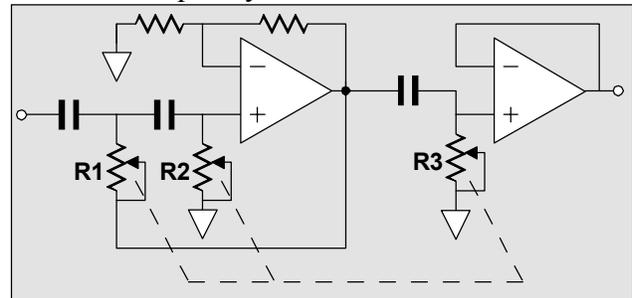


Two section 3rd order highpass filter



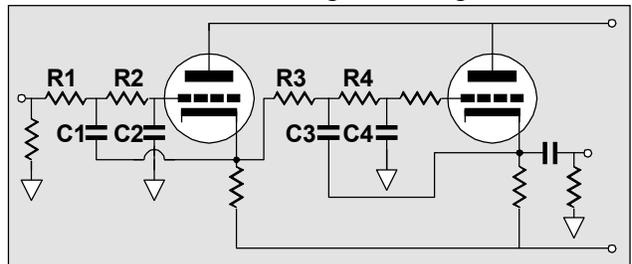
Single section 3rd order highpass filter

What advantage does one hold over the other? For the cathode follower based filters, little advantage exist other than the two section method having one less active device in the signal path. But if the buffers were replaced with amplifiers, then the two section method allows for all the resistors to equal each other. How is that an advantage? If all the resistors equal, then an adjustable crossover point can easily be had by using a three deck potentiometer to set the crossover frequency.

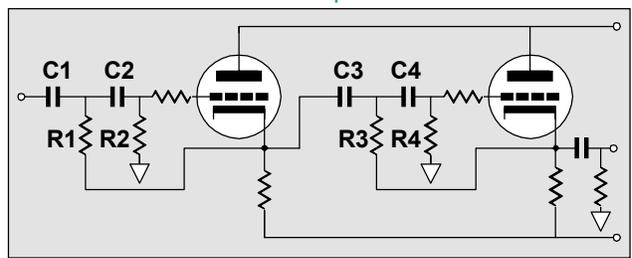


4th Order Filters

While 4th order filters can be made from a single section, it is much easier to cascade two 2nd order filters. Remember the Qs multiply against each other. Thus two Butterworth 2nd order filter with a Q of .707 will when cascaded yield a Q of .5, which is, by the way, the Q of the Linkwitz-Riley filter. So in order to make a 4th order Butterworth filter, one section's Q might be .84 and the second section would have to be also .84 to have the product equal .707.



4th order lowpass filter



4th order highpass filter

The Resistor and Capacitor Values

The table below gives all values for the 1st, 2nd, 3rd with one section, 3rd with two sections, and 4th order filters. The base frequency is 1000 Hz. To decrease the frequency, scale either the resistor or the capacitor values down by 1000/F, where F equals the desired crossover frequency.

To increase the frequency, scale either the resistor or the capacitor values up by F/1000, where F equals the desired crossover frequency.

1st Order Highpass & Lowpass

C1	.015915 μ F	R1	10k
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2nd Order Lowpass

	Butterworth	Bessel	L-R
C1	.02251 μ F	.013783 μ F	.015915 μ F
C2	.01125 μ F	.018194 μ F	.015915 μ F
R1	10k	10k	10k
R2	10k	10k	10k

3rd Order One-Section Lowpass

	Butterworth	Bessel
C1	.02215 μ F	.022198 μ F
C2	.05644 μ F	.031939 μ F
C3	.003221 μ F	.0056962 μ F
R1	10k	10k
R2	10k	10k
R3	10k	10k

4th Order Lowpass

	Butterworth	Bessel	L-R
C1	.01723 μ F	.01759 μ F	.02251 μ F
C2	.0147 μ F	.01614 μ F	.01125 μ F
C3	.04159 μ F	.02422 μ F	.02251 μ F
C4	.00609 μ F	.00933 μ F	.01125 μ F
R1	10k	10k	10k
R2	10k	10k	10k
R3	10k	10k	10k
R4	10k	10k	10k

NOTE

Do not scale both resistor and capacitor values at the same time (or the frequency will not change).

"Hey, these values don't match the ones in my textbook!" It turns out that there are two different ways to determine where the crossover frequency falls; the -3 dB frequency, or the degree of phase shift frequency. We chose the former; many books choose the latter. Our choice makes more sense for loudspeaker crossovers; their choice, for single filters.

2nd Order Highpass

	Butterworth	Bessel	L-R
C1	.01 μ F	.01 μ F	.01 μ F
C2	.01 μ F	.01 μ F	.01 μ F
R1	11,250	13,780	15,915
R2	22,500	13,380	15,915

3rd Order One-Section Highpass

	Butterworth	Bessel
C1	.01 μ F	.01 μ F
C2	.01 μ F	.01 μ F
C3	.01 μ F	.01 μ F
R1	11,433	11,430
R2	4,488	7,931
R3	78,628	44,470

4th Order Highpass

	Butterworth	Bessel	L-R
C1	.01 μ F	.01 μ F	.01 μ F
C2	.01 μ F	.01 μ F	.01 μ F
C3	.01 μ F	.01 μ F	.01 μ F
C4	.01 μ F	.01 μ F	.01 μ F
R1	17,227	14,400	11,250
R2	14,704	15,690	22,500
R3	41,587	10,460	11,250
R4	6,091	27,140	22,500

TCJ Filter Designer

Filter Schematic Output About

Frequency

Fc 1000 Hz

LP HP

1st 2nd 3rd 4th

Active Passive

SS Tube RC LCR

Phase + Phase -

Equal C B+/- PS 2 Sect.

Bessel

Circuit Elements

C1 R1 T1

C2 R2

.01819 μ F

Buffered Version Show Labels Show Values Show Results

10 k 10 k 2M 300 6N1P

13.78 nF .1 μ F 18.19 nF 2M 40k 1M

+3

Tube low-pass 2nd-order self-bias filter

Press to choose a second order filter

The Solution

The challenge facing GlassWare was this: what to do with the *Tube CAD Journal*? how to keep publishing it without charging for it? Some possibilities were to stop writing the journal, to charge a subscription fee, or to take on annoying banner ads. None of those options appealed to me. But the idea of writing small and inexpensive [companion software](#), the sale of which would allow me to continue to publish this journal for free, seemed like the ideal solution, as no one is required to buy the software, but those who do will bask in the satisfaction of helping keep this free journal alive.

The downloadable software is incredibly affordable, \$12.95 USD -- the price of a budget CD. A disk version is available for a few bucks more. And if you buy either during October 2001, you get an early bird \$3 discount: only \$9.95 USD. (For Windows 9x/Me/NT/2000.)

First TCJ Program

This journal's first companion program is *TCJ Filter Designer*, which lets you design a filter or crossover (passive, solid-state or tube) without having to check out thick textbooks from the library and without having to breakout the scientific calculator. This program's goal is to provide a quick and easy display not only of the frequency response, but also of the resistor and capacitor values for a passive and active filters and crossovers.

While the program's main concern is active filters, solid-state and tube, it also does passive filters. In fact, it can be used to calculate passive crossovers for use with speakers by entering 8 ohms as the terminating resistance. Covering tube-based filters would never even be contemplated at the mainstream EE software mills, but tube crossovers are a major part of this program; both buffered and un-buffered tube based filters along with mono-polar and bipolar power supply topologies are covered.

TCJ Filter Design is easy to use, but not lightweight, holding over 60 filter topologies and up to four filter alignments: Bessel, Butterworth, Gaussian, and Linkwitz-Riley.

Passive Filters

1. low-pass 1st-order RC filter
2. low-pass 1st-order LCR filter
3. high-pass 1st-order RC filter
4. high-pass 1st-order LCR filter
5. low-pass 2nd-order RC filter
6. low-pass 2nd-order LCR filter
7. high-pass 2nd-order RC filter
8. high-pass 2nd-order LCR filter
9. low-pass 3rd-order LCR filter
10. high-pass 3rd-order LCR filter
11. low-pass 4th-order LCR filter
12. high-pass 4th-order LCR filter

Solid-State Filters

1. low-pass 1st-order filter
2. low-pass inverting 1st-order filter
3. high-pass 1st-order filter
4. high-pass inverting 1st-order filter
5. low-pass 2nd-order filter
6. low-pass 2nd-order equal value capacitors filter
7. low-pass -inverting 2nd-order MFB filter
8. high-pass 2nd-order filter
9. high-pass 2nd-order equal valued resistors filter
10. high-pass -inverting 2nd-order MFB filter
11. low-pass 3rd-order filter
12. low-pass 3rd-order two-section filter
13. low-pass 3rd-order two-section equal valued capacitors filter
14. low-pass -inverting 3rd-order MFB filter
15. high-pass 3rd-order filter
16. high-pass 3rd-order two-section filter
17. high-pass 3rd-order two-section equal valued resistors filter
18. high-pass -inverting 3rd-order MFB filter
19. low-pass 4th-order filter
20. low-pass 4th-order two-section equal valued capacitors filter
21. high-pass 4th-order filter
22. high-pass 4th-order two-section equal valued resistors filter
23. low-pass -inverting 4th-order MFB filter
24. high-pass -inverting 4th-order MFB filter

Tube Based Filters

1. low-pass 1st-order filter
2. low-pass 1st-order self-bias filter
3. low-pass 1st-order self-bias buffered filter
4. high-pass 1st-order self-bias filter

5. high-pass 1st-order self-bias buffered filter
6. low-pass 2nd-order filter
7. low-pass 2nd-order self-bias filter
8. low-pass 2nd-order self-bias buffered filter
9. high-pass 2nd-order filter
10. high-pass 2nd-order self-bias filter
11. low-pass 3rd-order filter
12. low-pass 3rd-order self-bias filter
13. low-pass 3rd-order self-bias buffered filter
14. low-pass 3rd-order two-section filter
15. low-pass 3rd-order two-section filter self-bias
16. low-pass 3rd-order two-section self-bias buffered filter
17. high-pass 3rd-order
18. high-pass 3rd-order self-bias filter
19. high-pass 3rd-order two-section filter
20. high-pass 3rd-order two-section self-bias filter
21. low-pass 4th-order filter
22. low-pass 4th-order self-bias filter
23. low-pass 4th-order self-bias buffered filter
24. high-pass 4th-order filter
25. high-pass 4th-order self-bias buffered filter
26. Output coupling capacitor 1st-order filter

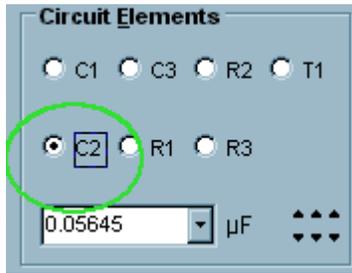
How to Use the Program

This program takes advantage of point and click interaction. The Fc frequency is entered in the drop-down box or the adjoining arrow buttons are pressed to move the frequency up or down to the desired value.

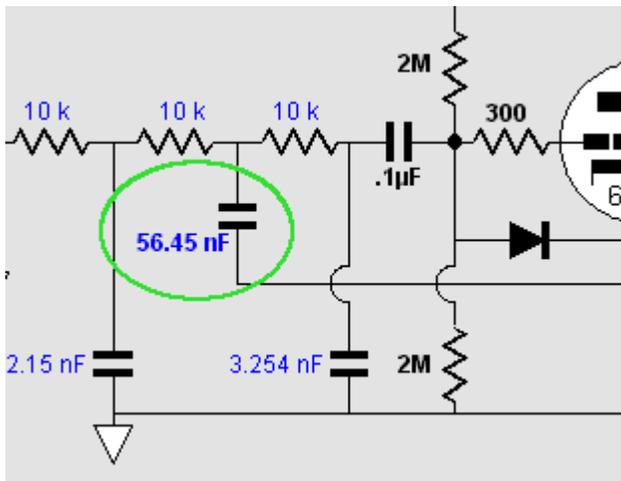
Clicking on any of the 17 filter choice buttons, causes the program to find and display the appropriate filter. And the drop-down box below the buttons is used to select the desired filter alignment.

Each time a new filter is chosen, the user-definable part list is displayed in the Circuit Element choice box of the program.

By selecting the circuit element's choice eyelet, the part's value is displayed in the drop-down box below it.



The value then can be changed by direct entry into the drop-down box or by choosing a value from its drop-down menu or by using the up-down buttons to the box's right. Once a circuit element is selected the schematic display show a bold face part label.

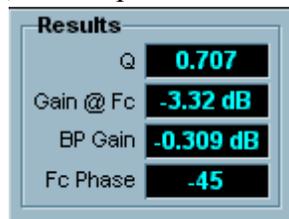


The circuit element can also be selected by clicking on the element's symbol in the schematic instead. Once the element is selected and its value changed, the program recalculates the other element's values and updates the schematic's display.

The Results and the Output

For most users it is not enough to have the program calculate the circuit element values, they need to also know what the resulting Q, Fc attenuation, bandpass gain, and Fc phase shift.

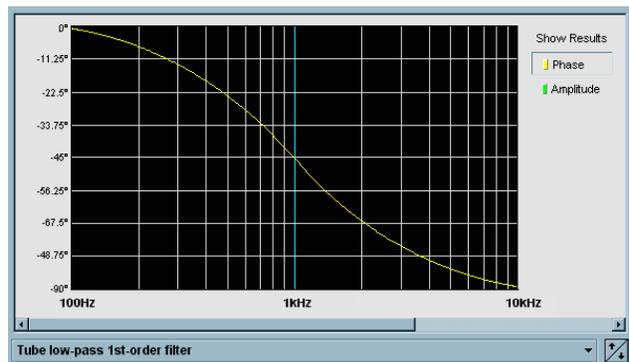
Pressing the Results button brings up the Results window that displays the important information.



This window can be moved about at will and hidden by pressing the Results button once again.



To graphically see the results only requires clicking on "Output" on the program's menu, as this will bring up a graph of either the filter's frequency response or its phase response, depending on which selection is made. Clicking on "Schematic" on the same menu returns the schematic into view.



Click on images to see enlargements

Moving the cursor over either graph will reveal in the hint-line either the phase and frequency at that point or the amplitude and frequency.



How to Buy TCJ Filter Designer

To purchase the program, follow the link to our new Yahoo store:

<http://store.yahoo.com/glass-ware>