CTCSS REJECT HIGH PASS FILTERS IN FM RADIO COMMUNICATIONS AN EVALUATION

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The response of the audio voice band high pass filter is evaluated in conjunction with the rejection of the CTCSS tone frequencies. The dual function of this filter in FM radio communications makes for conflicting requirements of passing quality voice audio, while rejecting the CTCSS tone frequencies that are in the low end of the audio band and can be heard if not rejected by the filter. The typical requirement of the filter is that the voice audio from 300 to 3000 Hertz be passed and rejection of the CTCSS band from 67 to 203.5 Hertz.

From an ideal world this requirement would not be a problem, but the real world of filters makes it a challenge to design. The real world of filters does not have sharp corners or go from pass to reject in 0 Hertz, thus a lot of issues. So how does the real world work? Filters have a corner frequency and that means that at that frequency, the response is down by –3 dB and is a point on the curve transitioning from flat to the slope toward the reject level of the filter. The slope determines how many Hertz it will take before the filter will attenuate the desired level for the reject frequencies. To illustrate this more, lets say one would desire the response level at 300 Hertz to be the same as at 1000 Hertz, then that means the –3 dB frequency must be lower than 300 Hertz. This can be done but that means that the upper frequency of the CTCSS band must also be lower which for some is not acceptable as the desire is to have a higher CTCSS tone – thus the conflict!

ABOUT ELECTRONIC FILTERS

In the electronic world, filters are a big topic so I plan to just point to that which is relevant to this paper. The topic of electronic filters is covered in many textbooks such as "Electronic Filter Design Handbook" by Arthur B. Williams also there are application notes such as Analog Devices AN-649. Filters that have a particular response curve have names like Butterworth, Chebyshev, and Elliptic or Cauer. These response curves are determined by mathematical functions that can be used to predetermine the response curves as needed by the designer. Typically these have been reduced to tables of coefficients, as the calculation is very complex. The implementation of these response curves can be done by many topologies. These topologies can be accomplished with passive components, passive components and amplifiers, switch capacitor devices, and digital methods. The use of op-amps for a filter is generally called an active filter. A particular name for one of the common topologies is "Unity-Gain Sailen-Key Active Filter". There are a plethora of topologies for the implementation of particular response curves.

THE RESPONSE CURVES

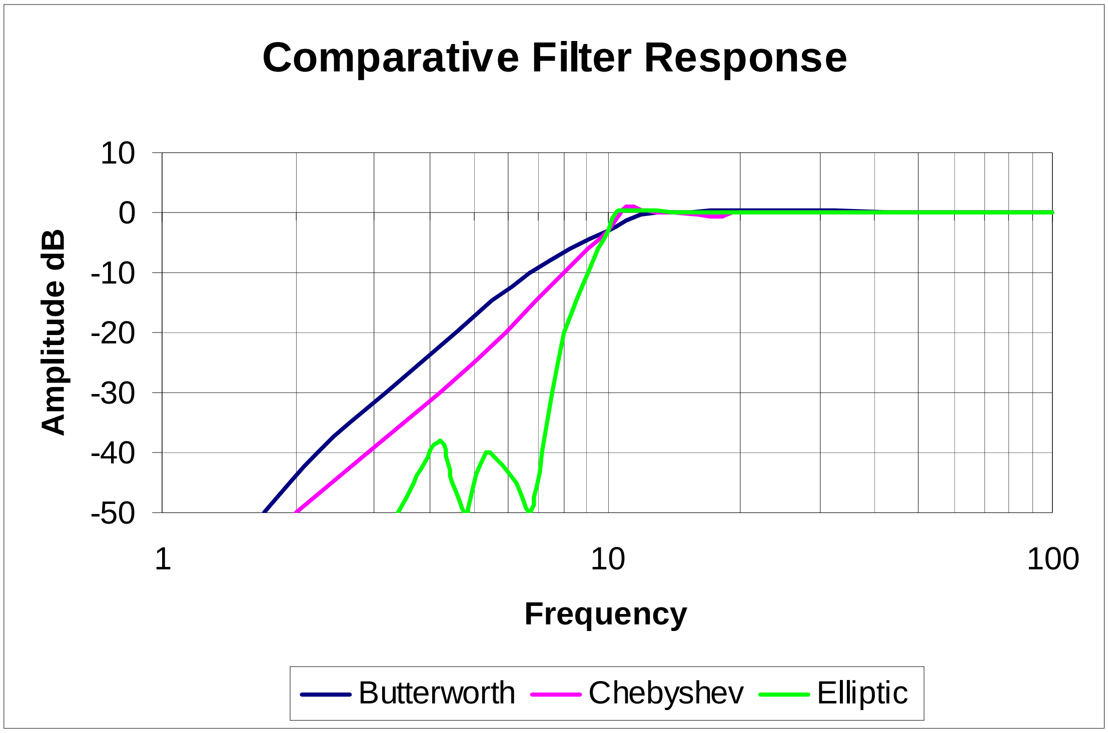


Figure 1 – Relative Comparative 3rd Order Filter Response Curves

As can be noted in figure 1, the relative response curves show the fundamental differences between the curves. For this application of rejecting a CTCSS tone and at the same time having the lowest flat audio response is the desired goal. For this plot, the frequency has been normalized to be 10 at the –3 dB or corner frequency of the HPF. Examination at this point will easily show that the response of the Chebyshev and the Elliptic filter is flat closer to the corner frequency than the Butterworth. From the rejection of CTCSS tones, the Elliptic filter is easily seen to be better. However the Elliptic filter is not typically used because of the additional complexity of more parts and nonstandard parts. It may be easy to implement an Ellipitic filter with a digital topology, which is not covered by this paper.

So what can be done to improve the overall response to meet the requirements of the application? Selection of filter parameters for each type of filter response will change the response curve. The order of the filter will change the steepness or transition band for all the different types. The larger the order number, the response will be steeper. The above nominal response curves are for 3rd order filters. The order refers to the number of poles for the filter; for example, a simple RC network is a 1st order filter. Another factor that will affect steepness is pass-band and or stop-band ripple, this is applicable to the Chebyshev and Elliptic filters. Thus the selection of a filter response along with the appropriate parameters can be made to meet requirements most of the time. A study of filters will show that this can be a complex topic as there are many aspects of filter design such as group delay, impulse and step response that are not covered here and is beyond the scope of this paper. Another factor in filter design is the input and output impedance requirements for correct filter response. In the RF world, this is often referred to as matching which is important for correct filter response as well as power transfer. In the audio world, matching is for correct filter response and seems to be left out of the filter description in a number of cases.

FM RADIO COMMUNICATIONS HIGH PASS FILTER

Five high pass filters were evaluated for this paper and the results plotted. The filters measured were – TS-32 & 64, Motorola Micor & MSR2000, and GE. The generator used was an HP3336B Synthesizer and the voltmeter was an HP 34401A. Reference level is 0 dB at 1000 Hz. The specific measurement process for each of the filters is described in the appendices following this paper. The comparison here is limited to the best representative response curve for each filter. In the comparison, the assumed nominal level for acceptable CTCSS tone rejection is –30dB. Also this comparison is not done with listening tests but response level comparison only.

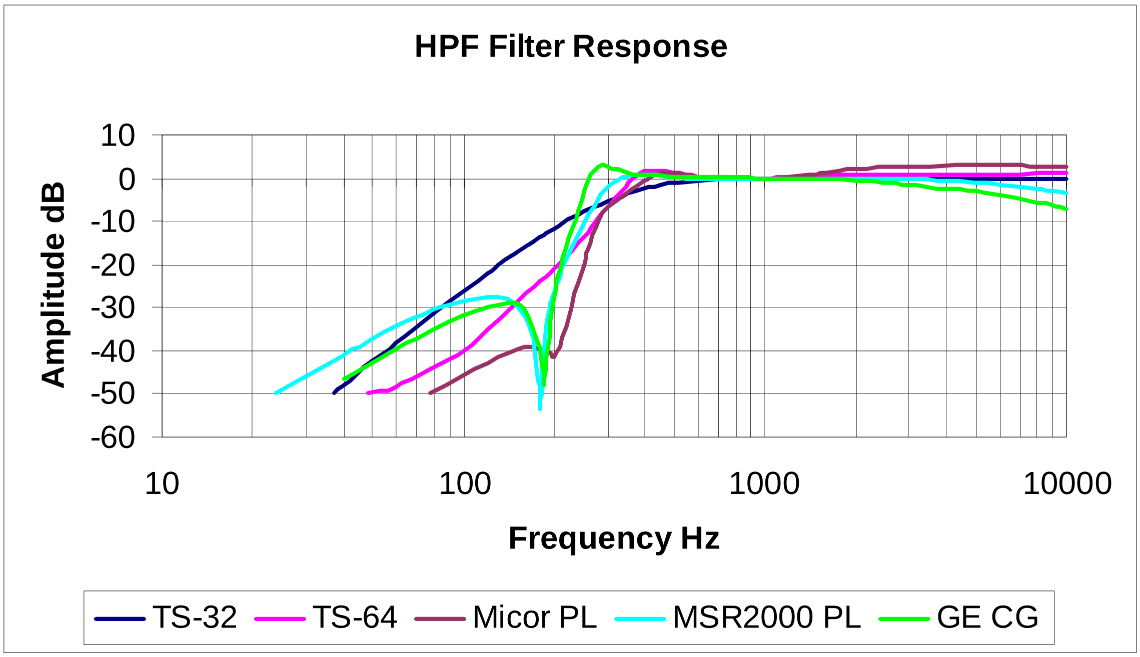


Figure 2 – Comparative Response of the Five Filters

This figure is a little busy but it gives the best picture as to the comparative performance of the filters.

Starting with the TS-32, it is a 3rd order Butterworth filter using the “Unity-Gain Sailen-Key Active Filter” topology and shows the smooth transition from pass band to stop band. This filter response shows that it is just barely acceptable and the CTCSS tone will need to be in the low frequency range.

The TS-64 is a 3rd order Chebyshev using the “Unity-Gain Sailen-Key Active Filter” topology with a nominal 2db ripple in the pass band. This is a nice improvement over the TS-32 as the nominal pass band response is closer to the corner frequency of the filter, also the stop band for CTCSS moves up and allows for higher tone frequencies to be attenuated.

The other filters are a sort of hybrid as they sort of look like an elliptic filter, but as far as I can tell, these are not true elliptic-function filters. The Micor filter consists of inductors and capacitors while the MSR2000 uses an active circuit called a gyrator to simulate an inductor. Other than for the active circuit to simulate an inductor, both are an L-C-L configuration with input and output coupling capacitors. The GE filter combines an active notch filter with a high pass filter. (Note: the schematic and manual calls it a low pass but I feel this is an error, as I do not see the low pass function.)

The Micor filter response definitely has a higher frequency of attenuation for the CTCSS tones, but the audio pass band is nominally the same as the TS-64.

The MSR2000 and GE have very similar response curves with the GE curve having its pass band flatter closer to the –3dB point. The notch is about 185 Hz and as such has good attenuation up to 200 Hz. But below the notch frequency, the response raises in amplitude and the attenuation in the 100 Hz range is less than the notch frequency attenuation. From a CTCSS stop band perspective, this filter may not be acceptable in the midrange and may account for some folks having CTCSS tone in the 185 Hz range.

CONCLUSION

From a pass band perspective, the GE CG filter has the lowest response to the corner frequency, but the overall rejection of the CTCSS tone band is somewhat lacking especially in the 100 Hz range. Overall it is the better filter from a response point of view than any of the filters measured, with the MSR2000 a very close second.

I designed a 5th Order Chebyshev filter with 1 dB pass band ripple for comparison. Below is the plot of the GE and a Chebyshev filter for a comparison.

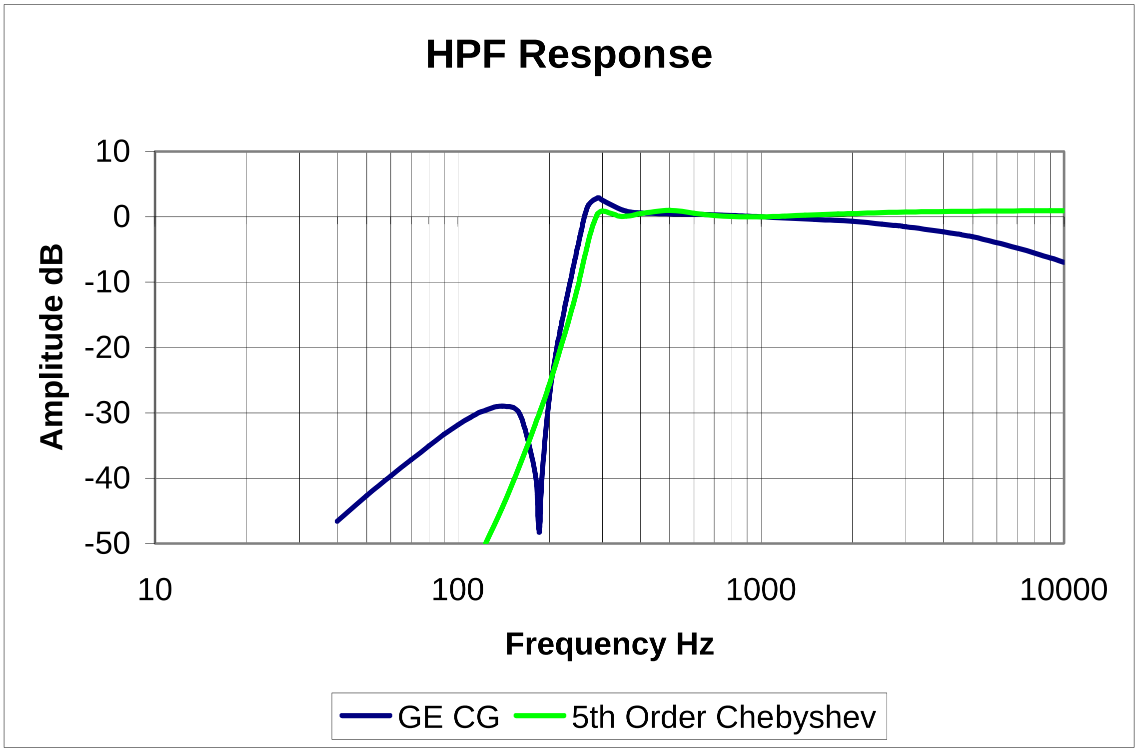


Figure 3 – Comparison of GE CG and 5th Order Chebyshev Filter

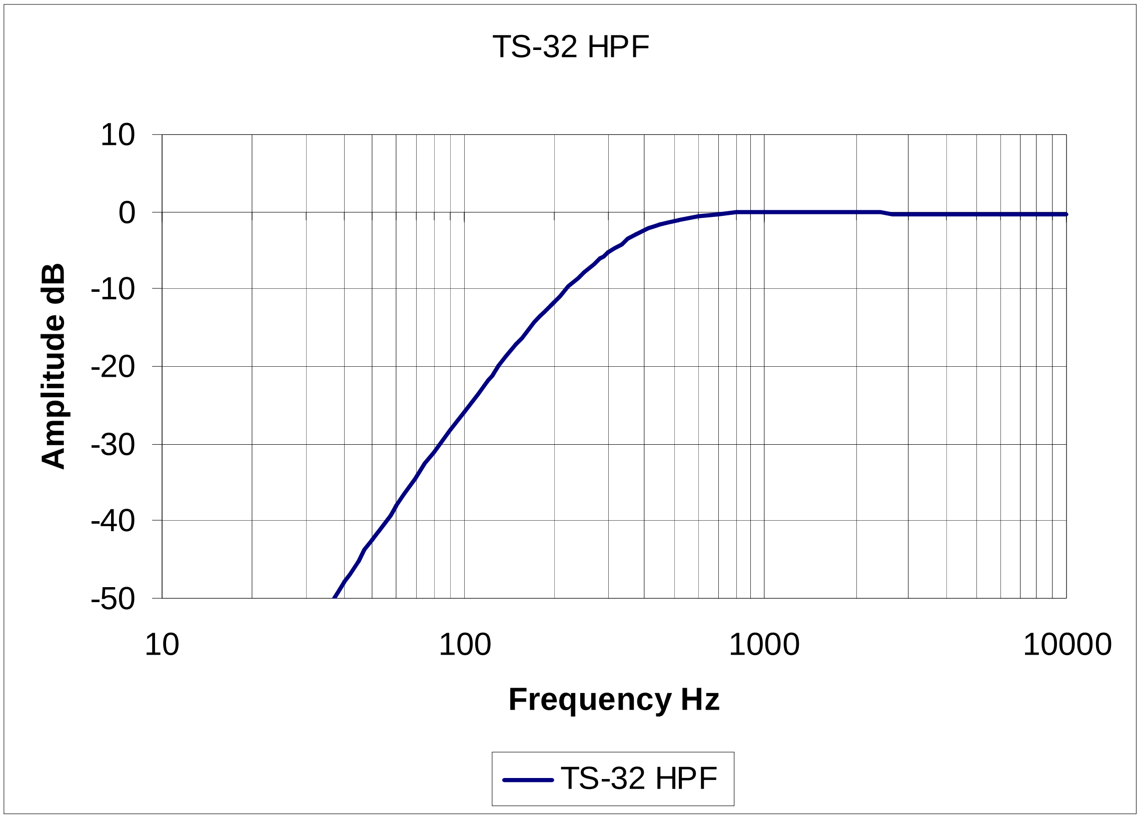
The corner frequency or –3dB point for the 5th Order Chebyshev filter is 275 Hz. From an overall performance point of view, the Chebyshev filter has as good of pass band response as the GE and better attenuation of the CTCSS tone frequency band. Thus it is a good candidate for those wishing good band pass down to at least 300 Hz with good attenuation of CTCSS tones below 200 Hz. CTCSS tones around 160 Hz and below are attenuated more than the GE filter.

I would like to thank the amateurs that donated filters to make this response comparison possible.

Appendix Index:
A – TS-32
B – TS-64
C – Micor PL
D - MSR2000
E – GE CG
F – 5th Order Chebyshev
G – Loudness Curves

Appendix A:

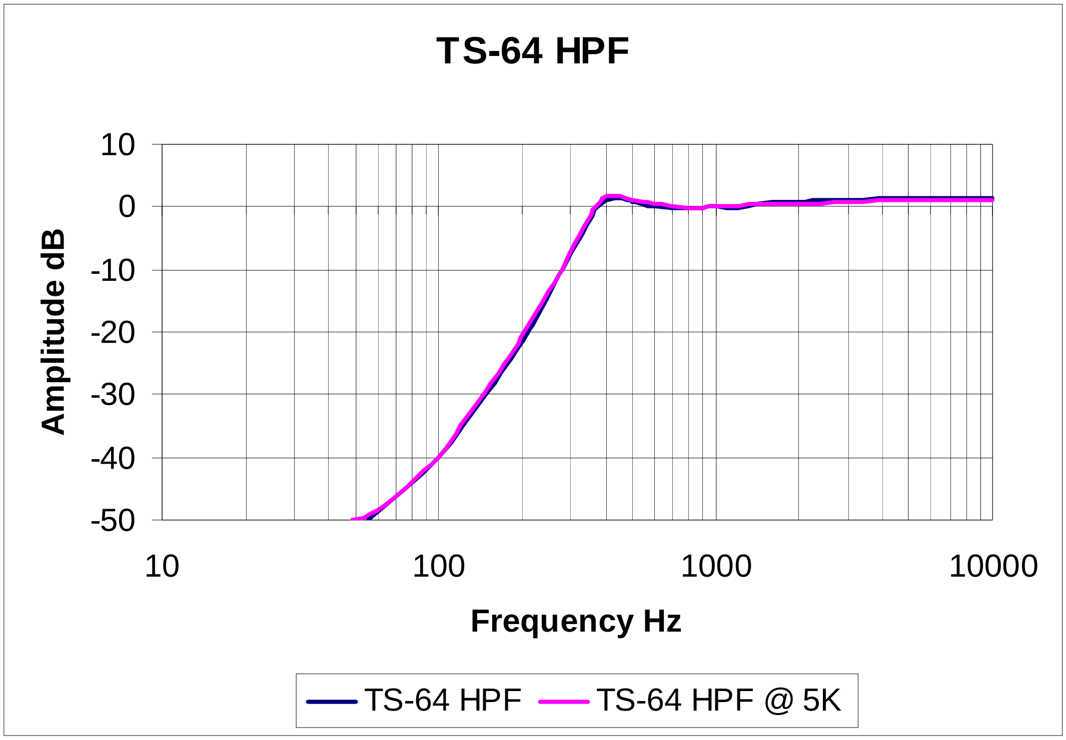
The TS-32 CTCSS Encoder/Decoder by Communication Specialists is no longer available but the schematic is available from their web site. The HPF is of the Sailen-Key Topology and is a typical 3rd Oder Butterworth filter.



The –3dB point or corner frequency is at 375 Hertz. Since the filter has high input impedance, varying the impedance of the driving generator in the 0 to 10K ohm range had no effect on the frequency response of the filter.

Appendix B:

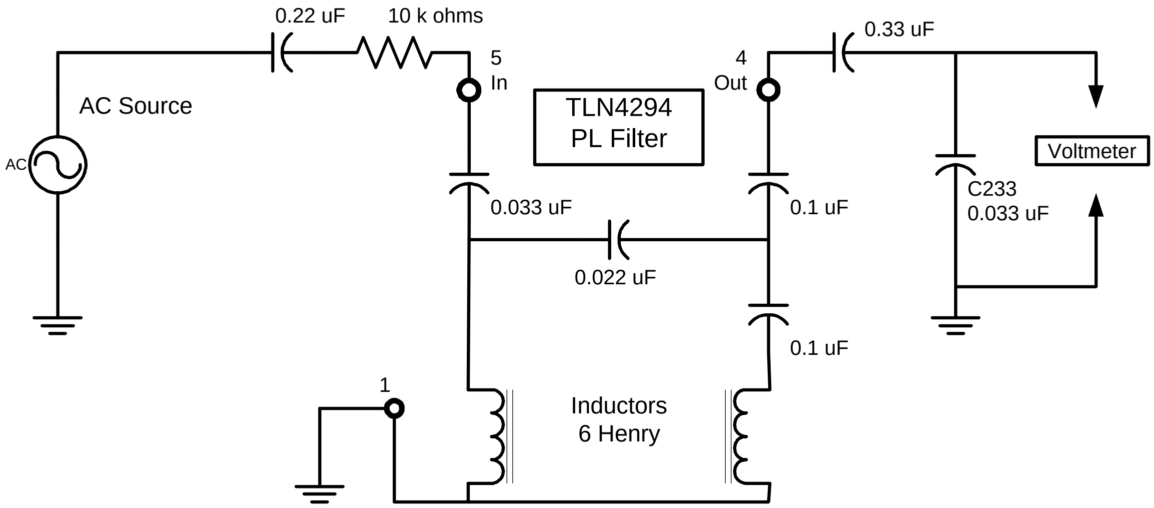
The schematic for the TS-64 CTCSS Encoder/Decoder is available from Communication Specialists web site. The HPF is of the Sailen-Key Topology and is a typical 3rd Order Chebyshev filter with pass band ripple of about 2 dB.



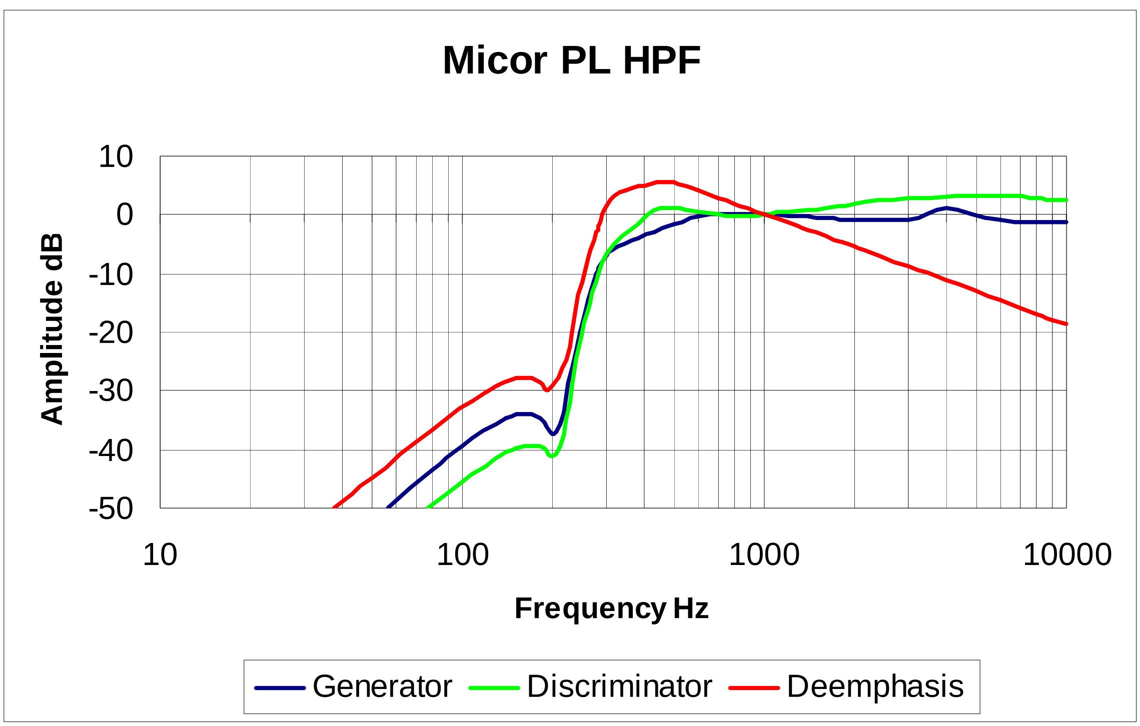
The –3db point or corner frequency is 335 Hertz. Note the lower frequency response in the pass band. Since the filter has somewhat lower input impedance, there is a difference in response between a 75 ohm generator and a 5K ohm generator. The difference is not large but is noticeable. Of course, as the generator or source impedance increases, the response will change even more.

Appendix C:

The response of the Micor PL high pass filter is a not a straight forward measurement because it is inside the deemphasis circuit.



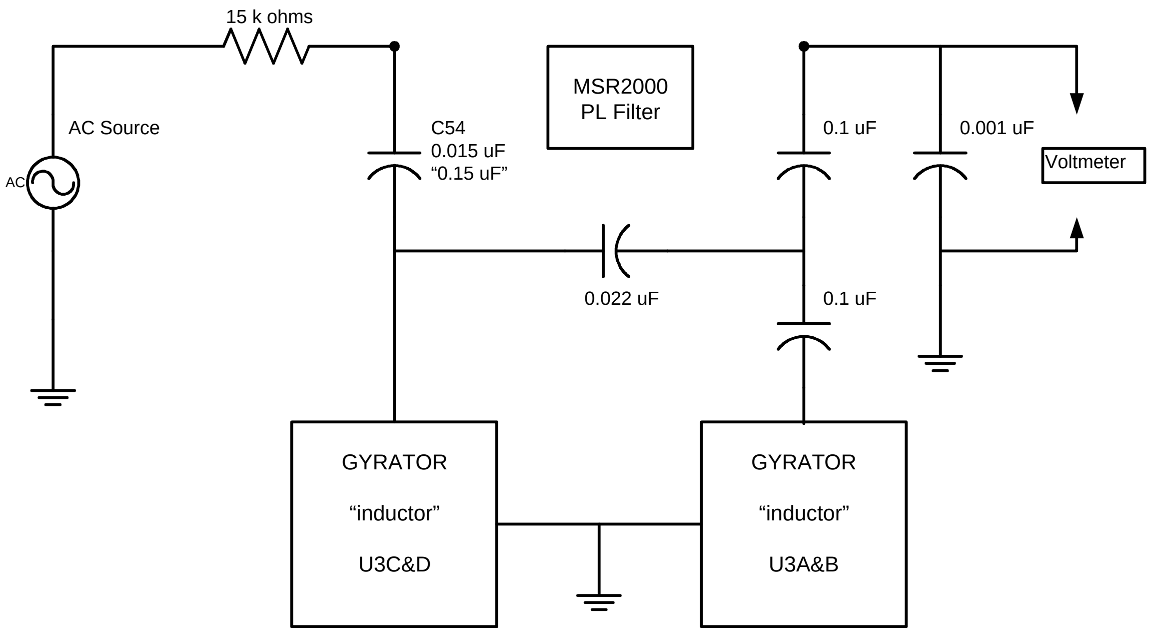
Filter response measurement circuit that shows connections of the AC Source and Voltmeter along with interface components to filter. The 10k ohm resistor and C233 0.033uF capacitor form the deemphasis circuit. Response measurements were made with the capacitor C233 connected and disconnected with the AC source a flat response generator. Also a response measurement was made from a source simulating a discriminator output with capacitor C233 connected.



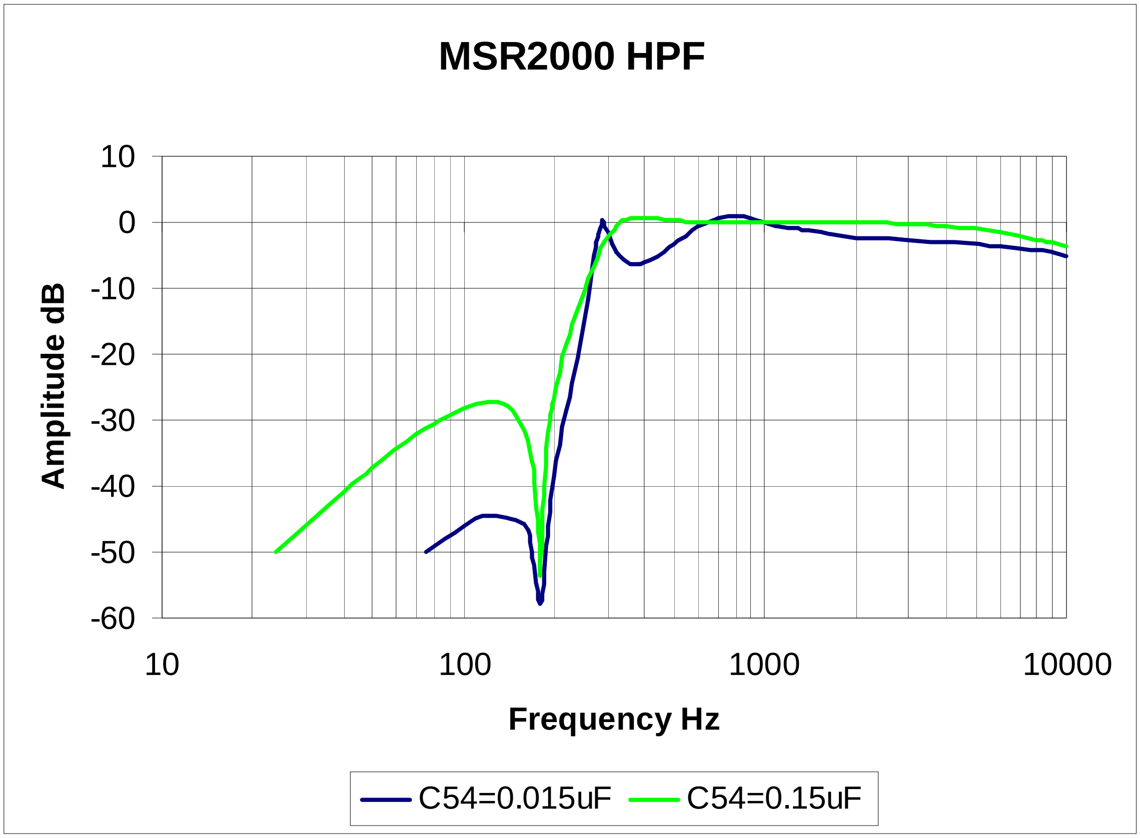
The simulator for the discriminator response had its preemphasis corner frequency at 250 Hz. The response curve shows a notch at a nominal frequency of 200 Hz. Ideally, the curve for the flat generator and the discriminator should be the same, but they are not, which shows that the system response curve of the filter may not be that which a system measurement would indicate. The “deemphasis” response shows the typical slope –6 dB per octave with the 10k ohm and 0.033 uF deemphasis circuit. With the deemphasis circuit in place, the discriminator source then shows the response of a transmitted PM signal resulting in a nominal flat audio response. The –3 dB point for the discriminator response is 350 Hz.

Appendix D:

The Motorola MSR2000 PL filter is similar in design to the Micor filter except for the use of gyrators to simulate the inductors.



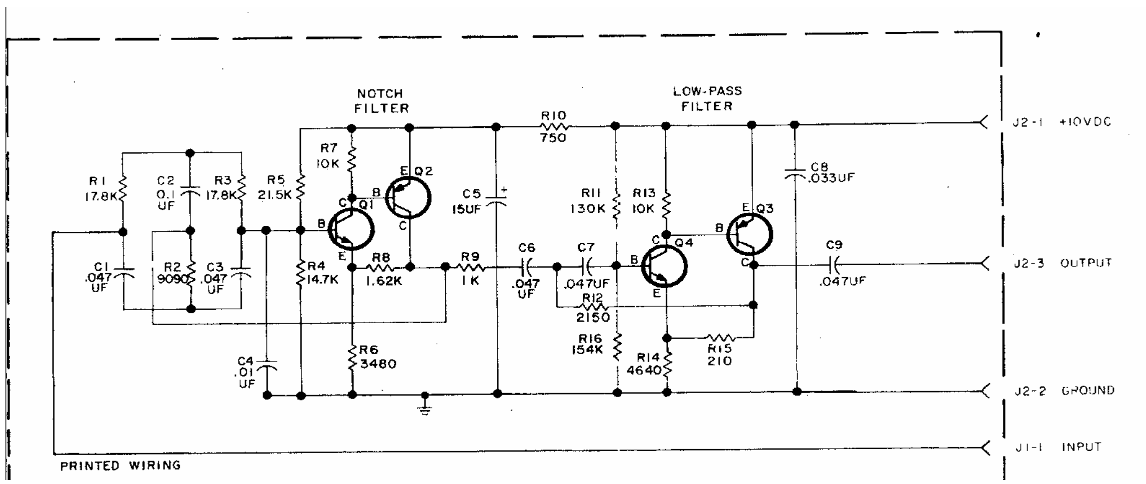
Filter response measurement circuit that shows connections of the AC Source and Voltmeter along with interface components to the filter. The schematic for the circuit with the gyrators is in the manual. Measuring the response of the filter with the value of 0.015 uF for C54 as stated in the manual yielded an unreasonable response. I assumed that there may be an error in manual and that the value should be 0.15 uF. If anyone has an actual board, it would be nice to measure the value to verify the correct value for C54. The circuit was duplicated from the schematic in the manual.



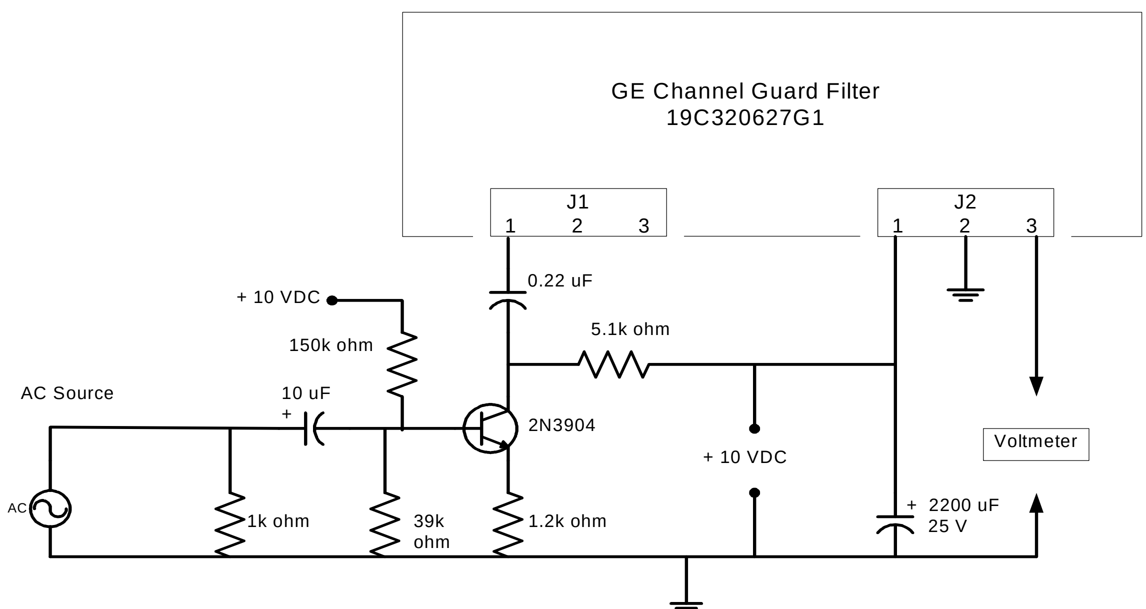
The frequency response curves for the two values of C54 shows what I feel is an unreasonable response for C54 = 0.015 uF. The response with C54 = 0.15 uF is the one I used in the main part of this paper. The notch frequency is a nominal 180 Hz and the –3 dB corner frequency is 300 Hz. As can be noted, the CTCSS tones around the notch frequency are highly attenuated but around 100 Hz they are attenuated a nominal 28 dB. Even though the notch is effective in allowing for a lower voice band response and higher CTCSS band width, this is accomplished at the expense of less overall attenuation of the CTCSS band.

Appendix E:

The GE CG filter board # 19C320627G1 is a combo of a notch and high pass filter. In the manual (LBI30727) the unit is described to have a notch and a low pass filter, which I feel is in error.

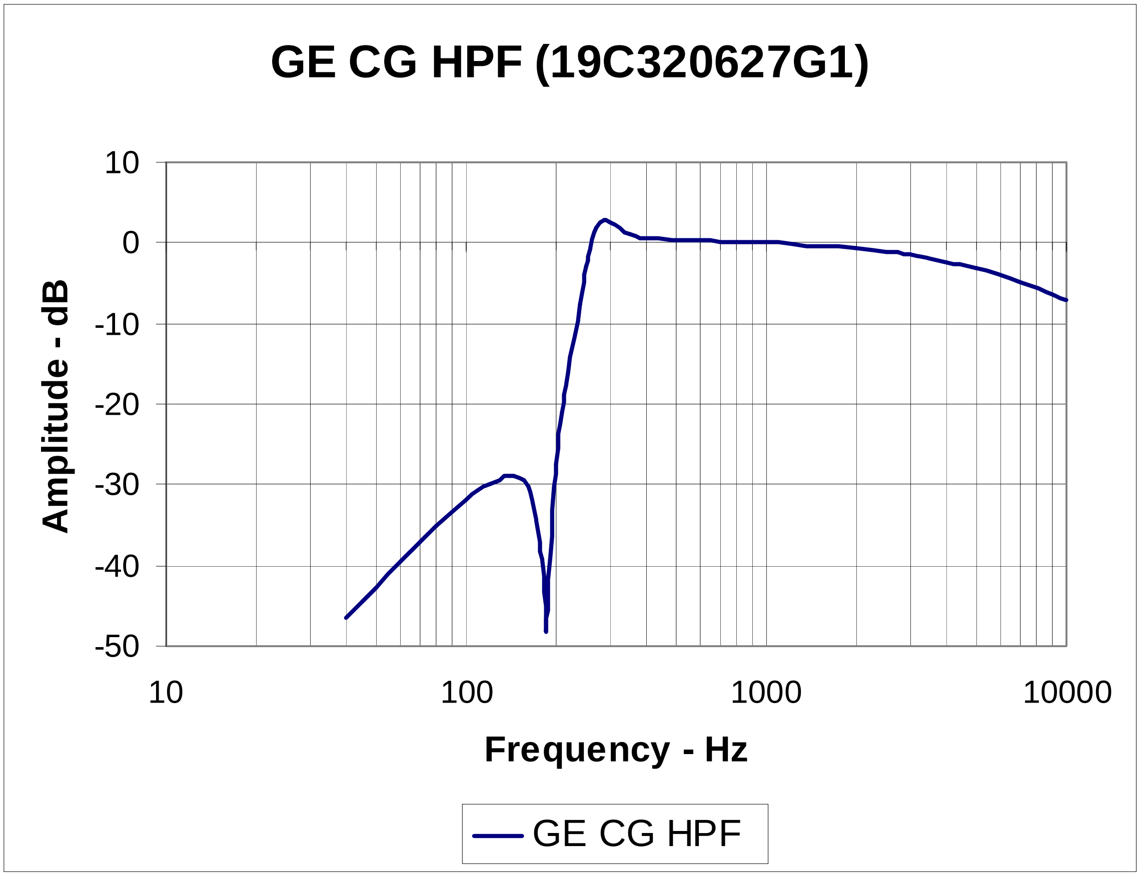


Above is the schematic from the manual showing the low pass filter identification. To test this filter, I built a circuit to replicate the driving circuit of this filter from a GE repeater manual.



Filter response measurement circuit that shows connections of the AC Source and Voltmeter along with the interface components to the filter.

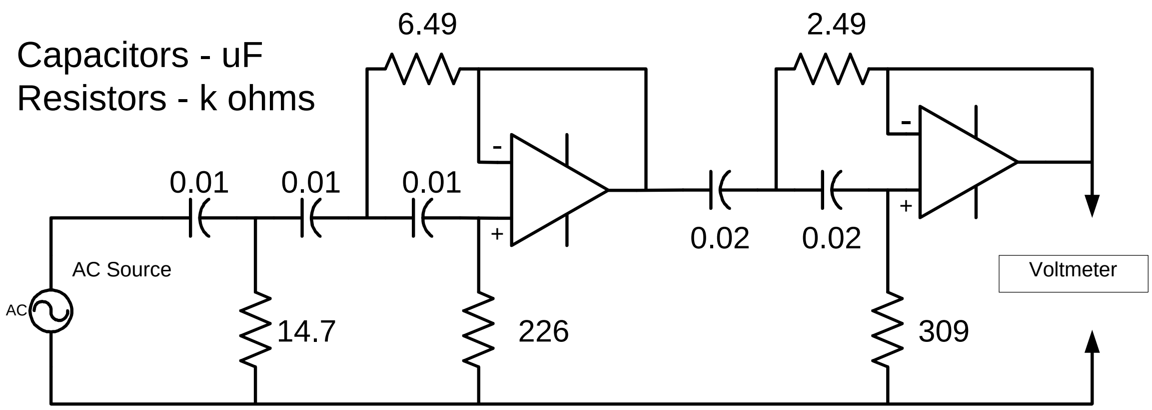
Response curve follows:



Overall this is the best curve for low-end pass band response and rejection of CTCSS tones of the five filters measured for this paper. The –3 dB or corner frequency is 253 Hz and at 205.3 Hz, the attenuation is –25 dB. The notch attenuation is –48 dB at 185.5 Hz. The attenuation is 29 dB around 140 Hz where the curve rises below the notch frequency.

Appendix F:

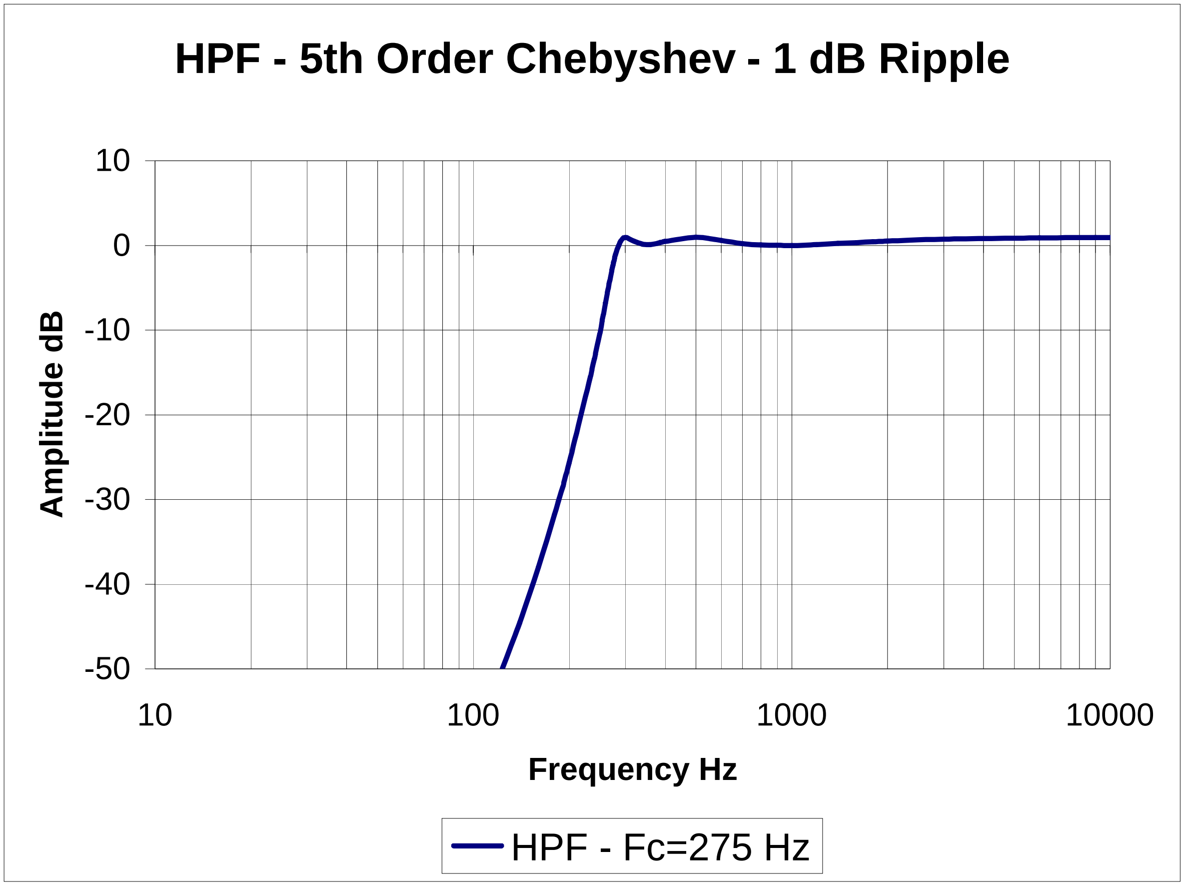
The 5th Order Chebyshev filter was used as a comparison to the filters measured. A pass band ripple of 1 dB was chosen to make the low end or the pass band response peak as close as possible to the corner frequency. The corner frequency is 275 Hz. The Unity-Gain Sailen-Key topology was used for the filter.



5th Order Chebyshev - 1 dB Pass Band Ripple - HPF

As in any higher order filter, the use of precision components is required to obtain the expected response. This filter was constructed with 1% resistors and capacitors. Also due to the high value resistors, the op-amps should be of the high input impedances types such as FET or CMOS input. Op-amp power and biasing are not shown in this schematic.

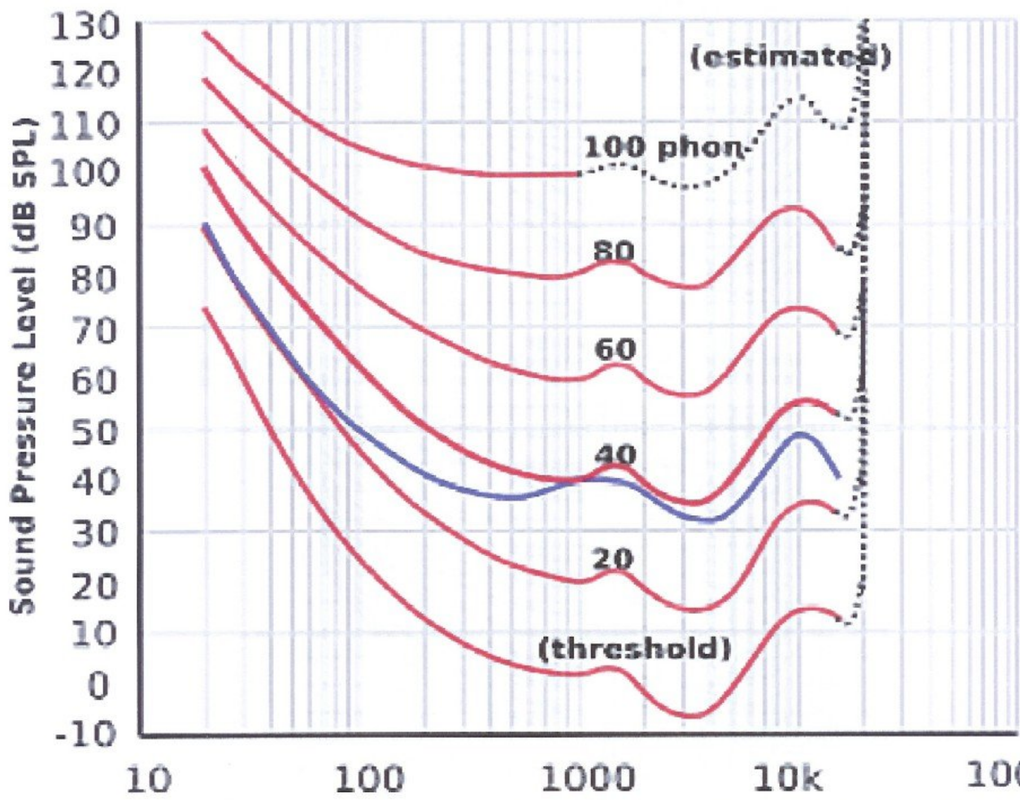
Resistors with 1% tolerance are readily available, but 1% capacitors are not. I did find 2% film capacitors that should work well but they are not surface mount.



Some data for the 5th Order Chebyshev filter is 275 Hz for the –3 dB or corner frequency. The attenuation for the stop band is –20 dB @ 220 Hz –30 dB @ 185 Hz.

Appendix G:

The response measurements of the filters are measured with a voltmeter and as such are voltage response levels and not actual hearing or listening response levels. The folks in the hearing or loudness business of sound have long had response curves that simulate the typical hearing levels of a human ear. These curves have been around since the early 1930's and have been standardized in recent time by ISO.



Equal-loudness contours (red) (from ISO 226 :2003 revisic
Original ISO standard shown (blue) for 40-phons

One of the items to note is that the ear's sensitivity to lower frequencies starts to decrease in the 500 Hz range depending on the actual loudness. This normal response of the ear has an effect on what folks hear as compared to the electronic measurements. It may be that for good listening the filter should have a more peaking response at the low end to compensate for the normal response of the ear.