

A Passive LC Audio Filter For Amateur Radio Use



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Introduction

External audio filters are sometimes used to improve the selectivity or enhance the audio quality of amateur radio receivers. These filters are usually implemented as op-amp active filters, switched-capacitor filters, DSP-based filters, or some combination thereof.

Another possible and much older filter implementation approach uses a combination of inductors (L) and capacitors (C) with no active components. Such a passive LC filter has several shortcomings:

- There is no gain through the filter, only loss. The extra loss can usually be compensated for by adjusting the volume control.
- The filter center frequency and bandwidth are difficult to change and are usually locked in to the user's preference at design time.
- The minimum filter bandwidth is constrained by the Q, or quality factor, of the non-ideal components, particularly the inductors. Nevertheless, the attainable bandwidth is adequate for most operating conditions.
- The passive LC filter is physically larger and heavier compared to other filter implementation methods. This limits its suitability for use in portable applications.

In spite of these drawbacks, passive LC filters do have a major advantage. Being entirely passive, they do not introduce the noise and distortion typical of many active circuits.

Passive LC filters can be quite effective in improving the audio from a receiver. Residual power supply hum can be virtually eliminated and background hiss originating from wideband high-gain amplifier stages is often greatly reduced. Lowering the background noise level makes it significantly easier to copy weak signals and also reduces operator fatigue. Harmonic distortion products can also be eliminated, particularly in the case of a narrow-band passive CW* filter.

For these reasons I have come to appreciate the passive LC filter as a useful station accessory even when used in conjunction with a modern high-performance receiver. Other radio operators have come to the same conclusion^{1,2}.

The design, analysis, assembly, and testing of a passive LC filter accessory for my own station is described herein. Observations and lessons learned from this project are documented so that others may hopefully benefit from them.

*For the non-ham readers, CW (or continuous-wave) is a synonymous term for Morse code in the context of amateur radio.

Special Acknowledgement

Edward E. Wetherhold, W3NQN, is a recognized authority and designer of high-performance filters for use by the amateur radio community. His filter designs cover the spectrum from audio through RF and are used in both transmitting and receiving applications.

His high-frequency bandpass filters are currently available for purchase from Array Solutions³. These filters are highly regarded and often chosen for use in world-class multi-operator contest stations where only the best is acceptable.

Starting in the latter half of the 1960's, he published a multitude of articles addressing the application of surplus telephone toroidal inductors, commonly known in the industry as loading coils, to audio filters for use in amateur radio applications. Detailed information was included so that his designs could be easily duplicated⁴⁻¹¹.

He arranged for the donation of a large quantity of these surplus inductors from the Chesapeake and Potomac Telephone Company of Maryland. The inductors were provided with the understanding that they would be distributed to radio amateurs at no cost except for packing and shipping expenses. Over a period in excess of thirty years he took on the task of distributing these inductors in accordance with this understanding. It is only recently that this supply of inductors has finally been exhausted.

Perhaps the most popular of his audio filter designs is his high-performance passive CW filter. He has published several variations of this design over the years but the basic filter performance has not significantly changed. Thousands of these filters have been built; their scarcity in the used marketplace is a testament to their desirability.

The audio filters used in my project have been leveraged from his designs.

In addition, he graciously agreed to review this document prior to release and has made numerous helpful comments and suggestions. It has been significantly improved thanks to his efforts.

Project Evolution

After reading numerous rave reviews about Ed Wetherhold's passive CW filter kit, a decision was made to purchase one. Unfortunately, his supply of surplus telephone toroidal loading coils had finally been depleted and the kit was no longer available. A new version using fixed-value potted inductors is in the works but at the time of this writing it has not been released.

After a thorough market search it became obvious that if a similar passive filter was to be obtained in the near term then it would have to be built from scratch.

For months an attempt was made to locate surplus telephone loading coils for use in this project with no success. New telephone loading coils could be purchased but they were both cost prohibitive and potted. The potting material is nearly impossible to remove without destroying the coil, so the inductance cannot be modified by adding or removing turns. This in turn severely limits filter design flexibility.

Molybdenum Permalloy Powder (MPP) toroidal cores are the preferred choice for filter inductors in the audio-frequency range. MPP cores could have been purchased^{12,13} but their maximum available inductance index (A_L) was lower than desired. A few calculations showed that well over 500 turns would be required to achieve typical desired inductance values. Winding this many turns manually would be a daunting task. MPP cores were also found to be expensive in small quantities.

Finally a decision was made to proceed with the project using ferrite toroidal cores, specifically the FT-114-77. A small quantity of these cores was purchased from Amidon¹⁴ and shipped to Torelco¹⁵ to be wound.

Once the wound cores were delivered, the very first filter prototype was assembled on a crude breadboard, literally a piece of cardboard cut from a shipping box. It was a CW filter, designed with a center frequency of 600 Hz and a bandwidth of 150 Hz. A five-pole, 1- dB ripple Chebyshev design was selected to achieve a sharp roll-off characteristic.

It worked reasonably well but was plagued with ringing. Static crashes on the lower bands were especially bothersome as they created echoes, making it even harder to copy desired signals than without the filter. Clearly this was not the desired result!

In an attempt to eliminate the ringing, the design was modified to have a Butterworth response characteristic and the bandwidth was increased to slightly over 200 Hz.

Making these changes meant several cores needed to be rewound. This time I chose to wind the cores manually. It proved to be a lengthy and tedious chore even though less than 200 turns per core were needed due to the higher A_L of the ferrite material.

Some quick testing showed this design with relaxed specifications produced the desired result. The filter was then assembled on a piece of pad-per-hole perfboard as shown in Figure 1.

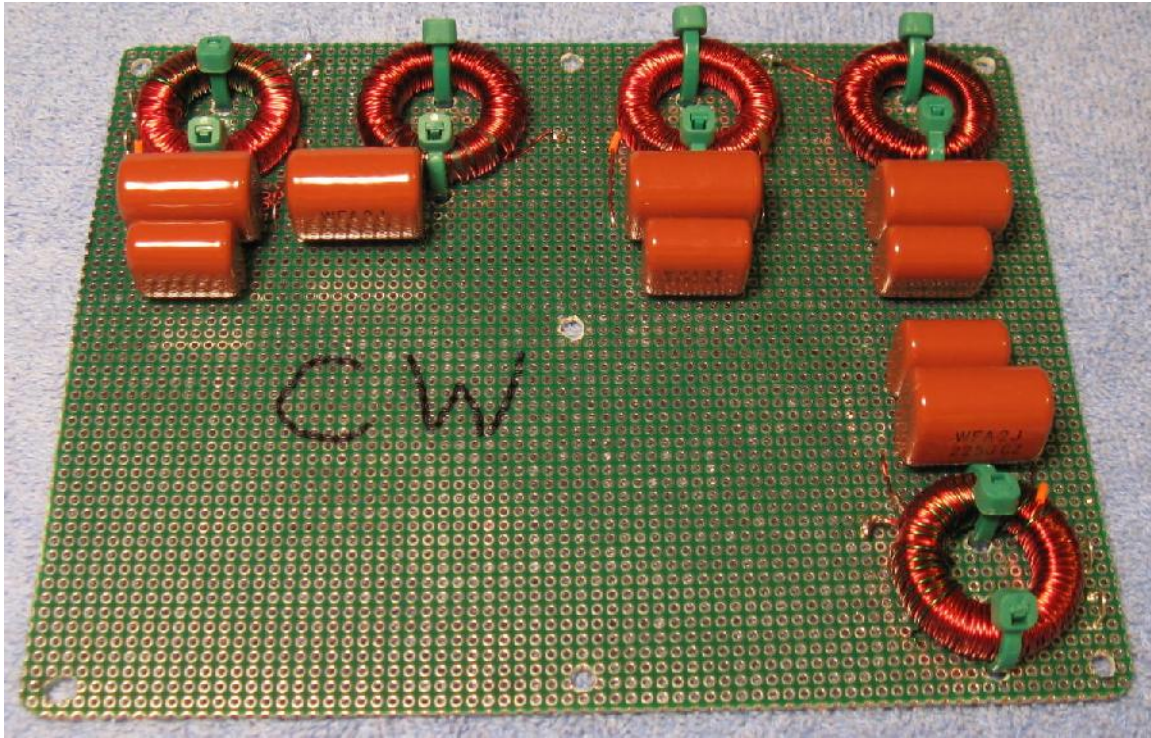


Figure 1. CW filter built using ferrite toroidal cores.

With the ringing no longer present, the filter made a noticeable improvement in the ability to copy weak signals. Given these encouraging results, a five-pole filter for voice use was then built as shown in Figure 2.

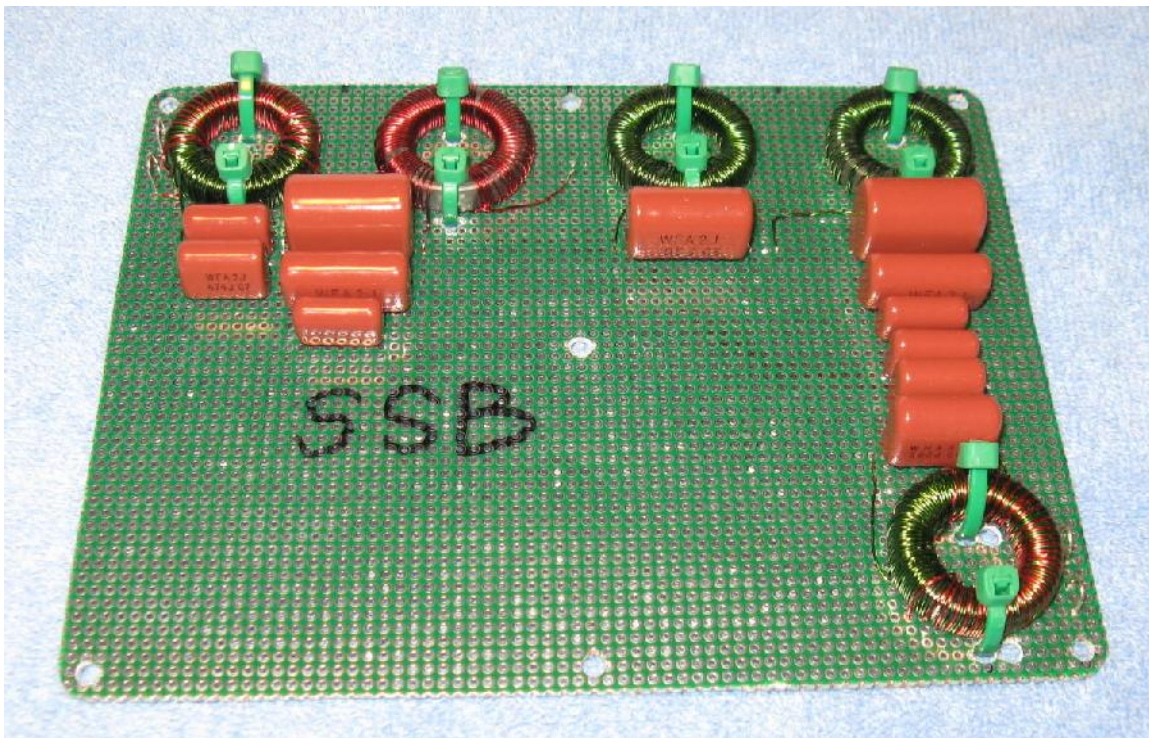


Figure 2. Voice filter built using ferrite toroidal cores.

Some minor detuning over large temperature variations was observed during bench testing. In particular, the CW filter response curve shifted by approximately 30 Hz after exposure to a heat gun for several minutes. But it was almost too hot to touch then.

The project was assembled in a Ten Tec¹⁶ TPB-49 enclosure and placed in service. It worked as desired, although there was some tendency for the inductors to saturate and cause distortion at moderate-to-high volume levels.

Shortly thereafter, a small quantity of old-stock unpotted telephone loading coils was discovered and purchased from an individual. Unfortunately, this supply was very limited and no additional loading coils are available from this source.

The project was then modified to use these inductors, particularly since they had MPP cores. The inductor characteristics were measured as described later and the filter designs were revised as needed to effectively utilize them.

In the process, the voice filter was changed from a five-pole design to a seven-pole design. This was done in an attempt to further improve out-of-band rejection, particularly above 3 kHz.

The revised CW filter built using the telephone loading coils is shown in Figure 3. Figure 4 shows the similarly revised voice filter installed in the enclosure.

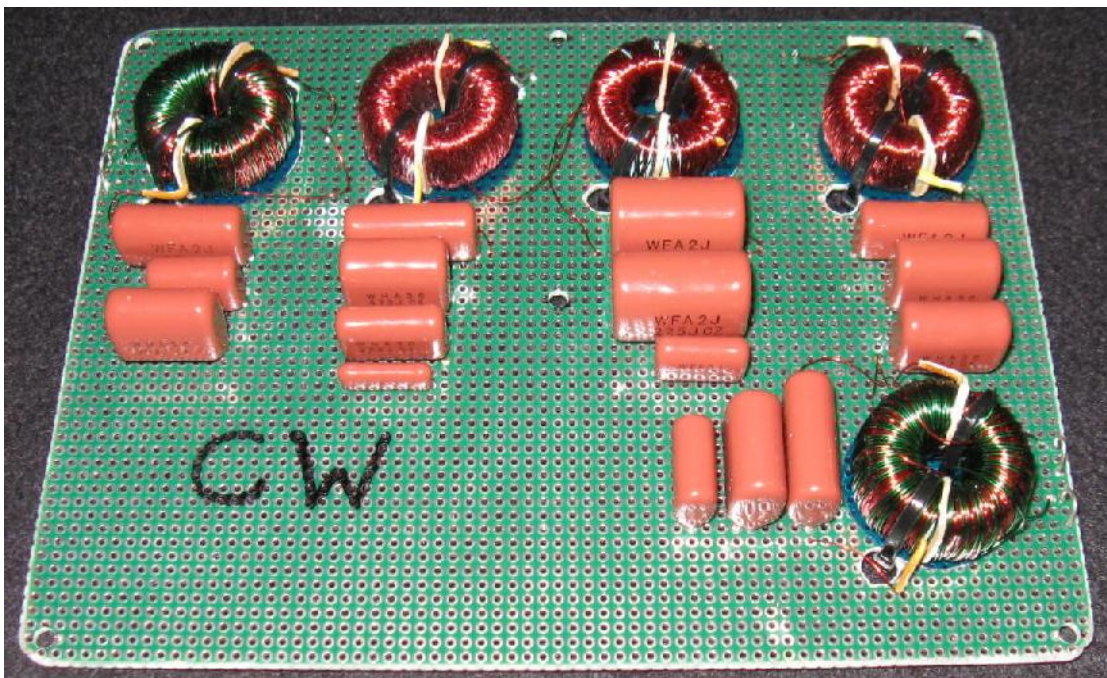


Figure 3. CW filter built using telephone loading coil inductors.



Figure 4. Voice filter built using telephone loading coil inductors, installed in enclosure.

The remaining undesirable side effects were eliminated. The inductors no longer saturated, even at high volume levels, and there was no observable detuning with large temperature variations.

Component Notes

Optimum filter performance depends upon the usage of components suitable for filter applications. Accuracy and stability of inductance and capacitance values over the expected operating temperature range is of primary importance to prevent detuning and associated performance degradation.

In addition, the component Q's must be sufficiently large to achieve the desired filter frequency response and to minimize insertion loss. As a practical matter the Q of an LC resonant circuit at audio frequencies is dominated by losses in inductors. Therefore, capacitor Q's can generally be ignored.

Capacitors

The Panasonic ECWF(A) and ECWH(A) polypropylene film capacitor series were chosen for this application. These capacitors are stable, readily available in the range of values needed, and not excessively expensive. They can be purchased individually or in kits of assorted values from Digikey¹⁷ as stock numbers ECWFA-KIT-ND and ECWHA-KIT-ND, respectively.

Capacitor voltage ratings are not a major issue but should be considered. Since a transformer will be used to match the receiver output impedance to that needed by the filter, a corresponding increase in the signal voltage can be expected. This could be an issue if low-voltage-rating capacitors are used. The selected Panasonic capacitors are rated for hundreds of volts.

Any capacitance value needed within reason can be obtained by simply connecting an appropriate mix of standard-value capacitors in parallel.

Inductors

As mentioned previously, MPP toroidal cores are the preferred choice for filter inductors in the audio frequency range. They are the most stable with respect to temperature and AC flux variations, have low losses, and are less likely to saturate than other core materials. They are also the most expensive.

Telephone loading coils use MPP cores almost exclusively. However, a reference to ferrite core loading coils has been noted so there is some probability that not all loading coils have MPP cores¹⁸. Western Electric pioneered the development of and was heavily invested in MPP for loading coils^{19,20}, so any Western Electric loading coils obtained are virtually certain to have MPP cores.

Millions of telephone loading coils were manufactured and fielded. Unfortunately they are extremely difficult to obtain now. The telephone plant has been modernized to reduce maximum subscriber line lengths and to support digital communications. This has diminished the need for loading coils.

It may still be possible to find surplus loading coils at certain independent telephone companies, however. Groups of loading coils were often placed in sealed containers called “pots” and the entire assembly was known as a “load pot.” Knowledge of this terminology may be useful when inquiring about availability.

Many telephone loading coils are potted. The nearly indestructible potting material makes it impossible to adjust their inductance by adding or removing turns. Therefore, unpotted coils are preferable for maximum filter design flexibility

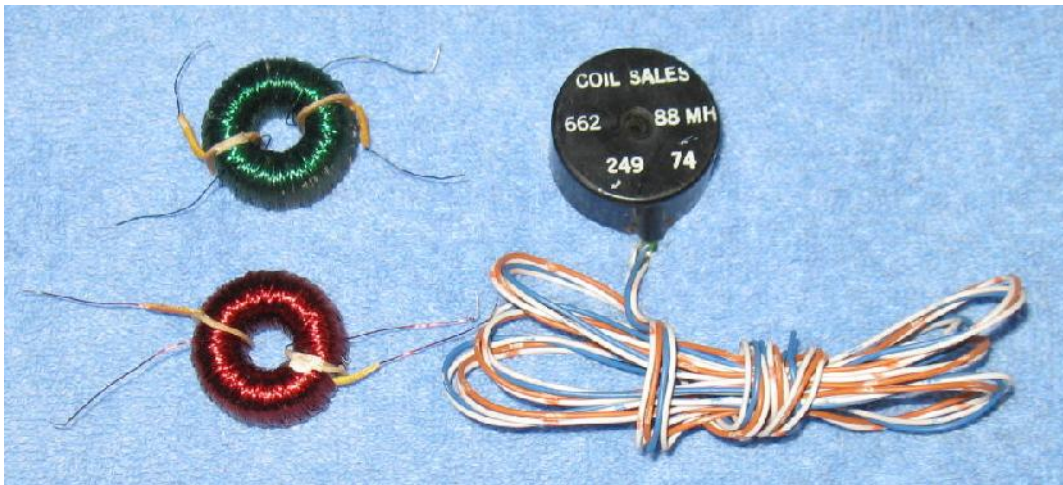


Figure 5. Unpotted loading coils (left) and potted loading coil (right).

Telephone loading coils were typically wound using one of the two winding methods illustrated in Figure 6.

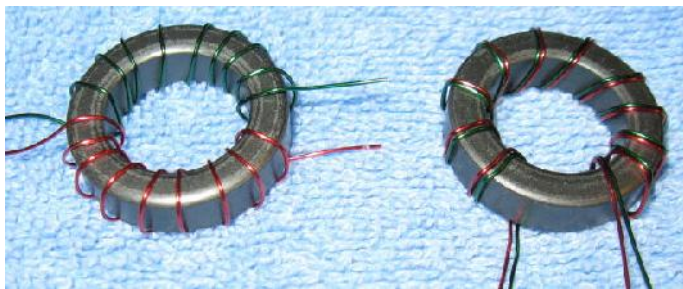


Figure 6. Split winding method (left) and bifilar winding method (right).

Loading coils with split windings usually have two pieces of cardboard to keep the windings physically separated. The unpotted loading coils shown in Figure 5 have split windings.

In a filter application the two windings are usually connected in series, thus forming one larger winding with a center tap at the point where the two windings are connected together.

If turns are removed to adjust the inductance, an equal number of turns should be removed from each winding to maintain the center tap position. Bifilar-wound coils are preferable as this balance is automatically maintained as turns are removed.

Tolerances for A_L should be considered when calculating the number of turns required to achieve a desired inductance. Simply winding or unwinding a predetermined number of turns may or may not result in the inductance being close enough for the filter requirements.

If the A_L is unknown it's better to start off with a known excess number of turns and remove them as necessary to obtain the desired inductance, making measurements in the process.

Telephone Loading Coil Inductor Characterization

The purchased telephone loading coil inductors mentioned earlier were characterized by measuring their inductance, series resistance, and Q values with a recently-calibrated LCR meter. The measurements are presented in Table 1.

Inductor	Winding 1			Winding 2			Both Windings in Series		
	Inductance (mH)	Q	Resistance (ohm)	Inductance (mH)	Q	Resistance (ohm)	Inductance (mH)	Q	Resistance (ohm)
1	21.86	20.5	4.02	21.93	20.7	4	82.42	38.2	8.14
2	21.7	17.5	4.68	21.7	17.7	4.6	81.3	37.9	8.08
3	21.9	20.6	4.01	21.9	20.7	4	82.1	38.1	8.1
4	22.1	20.7	4	22	20.4	4	82.6	38	8.2
5	22.2	21	4	22.2	21	4	83.7	38.3	8.3
6	22	20.6	4	22	20.6	4	82.3	38	8.2
7	22	21.2	3.9	21.9	21.2	3.9	82.4	38.3	7.9
8	22.4	20.9	4	22.1	20.7	4	83	38.4	8.2
9	22.1	21.4	3.9	22.1	21.1	3.9	82.5	39.3	7.9
10	22	21.3	3.9	21.9	21.3	3.9	82.7	39.4	7.9
11	22	21.3	3.9	22	21.5	3.9	82.8	39.6	7.9
12	22.1	21.2	3.9	22.2	21.1	4	83.5	39.2	8
13	22	21	4	22.1	21	4	82.9	38.8	8.1
14	22.3	20.8	4	22.3	17.6	4.8	84	38.8	8.2

Table 1. Telephone Loading Coil measurements.

All measurements were taken at 600 Hz.

The measured values matched fairly well, although the inductance readings were slightly lower than the expected 88 mH standard value.

A twenty-turn test winding was added to Inductor #1 and found to measure 61.3 uH. From this, the core inductance index A_L was calculated using the formula

$$A_L = L / N^2$$

where L is the inductance in nH and N is the number of turns.

$$A_L = 61300 \text{ nH} / (20 \text{ turns} * 20 \text{ turns}) = 153 \text{ nH} / \text{turn}^2$$

This value of A_L was used in subsequent design calculations.

Next, the total number of turns in the inductor was estimated using the same equation rearranged to solve for N, with the total measured inductance substituted:

$$N = (L / A_L)^{1/2} = (82,420,000 \text{ nH} / 153 \text{ nH} / \text{turn}^2)^{1/2} = 734 \text{ turns.}$$

The inductor wire diameter was measured and found to correspond to 28 AWG. Finally, the length of a single turn of wire was measured to be approximately 1.8 inches.

Design Procedure

The filter design procedure is described in this section using both the CW and voice filters as examples. Only the telephone loading coil inductor core designs are discussed, although the design approach is also applicable for other inductor types.

Modern Filter Design

The filters were designed using the “modern network synthesis” method. This method is based on usage of pre-calculated and normalized lowpass filter tables and response curves.

A response curve is first selected that meets the requirements, and then normalized lowpass filter element values are obtained from a corresponding table. If necessary, the lowpass filter prototype is transformed into another form such as highpass, bandpass, or bandreject.

For a lowpass-to-bandpass transformation, the lowpass shunt elements become parallel-resonant LC circuits and the lowpass series elements become series-resonant LC circuits. Each such resonant LC circuit is referred to as a *resonator*.

The normalized element values are then scaled for the desired center frequency, bandwidth, and termination impedances using simple equations.

Filter tables and design procedures can be found in many references. Chris Bowick’s [RF Circuit Design](#)²¹ covers the topic in terms easy for the layman to understand and utilize, complete with examples. It was used as a reference for this project.

The calculated component values vary according to the input design parameters. It is therefore possible to select convenient component values by making adjustments to parameters such as bandwidth and termination impedances.

A spreadsheet was created so that such design adjustments could be made quickly and easily. Screen shots of this spreadsheet are included in the following sections.

Filter Topology and Impedance Transformation

As shown in Figure 7 (A) and (B), either a series-input or a shunt-input form of the bandpass filter could have been used.

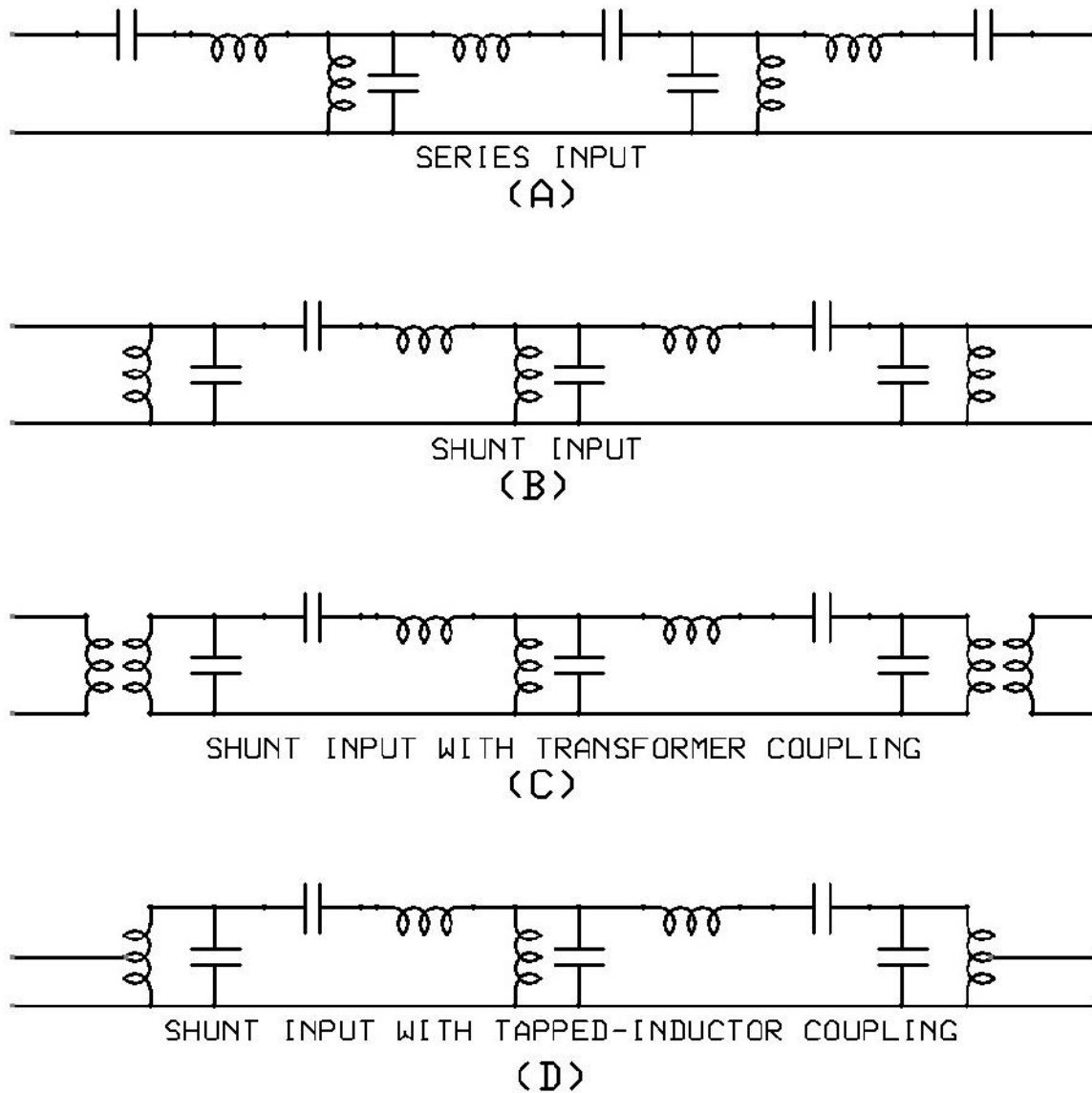


Figure 7. Candidate bandpass filter topologies and coupling methods, five-section filter shown.

One advantage of the shunt-input topology is the ease with which external impedance matching can be accomplished by configuring the outside resonator inductors to be transformers or autotransformers. This can eliminate the need for external matching transformers.

In Figure 7 (C), an additional winding is added to the each of the outside inductors for impedance matching. This matching approach is used for both filters in my project.

In Figure 7 (D), taps have been added to the outside inductors to form autotransformers. This approach eliminates the need for additional windings, but the taps must be located at the proper place to achieve the desired impedance matching.

Adding a tap to a pre-wound coil can be quite a task. However, an inductor fabricated from a telephone loading coil already has a tap located at the center. The center-tap location constrains the internal-to-external impedance ratio to 4:1. This is because the turns ratio of a center-tapped transformer is 2:1, and the impedance ratio of a transformer is the square of the turns ratio.

This technique can be used to transform high resonator termination impedances down to lower intermediate values. For example, an 800-ohm internal filter termination impedance can be transformed down to 200 ohms through use of a center-tapped resonator inductor. In turn, this allows a standard 200:8-ohm external transformer to be used to complete the matching to the lower receiver or speaker impedance.

In the filter circuits shown above, all resonators throughout the filter share the same termination impedance value used for calculating component values.

It is possible to transform impedances within the filter so that different resonators “see” different termination impedances. This can enable more convenient component values to be selected.

One way to accomplish this is to use the same tapped-inductor matching approach just described, but applied within the filter as shown in Figure 8.

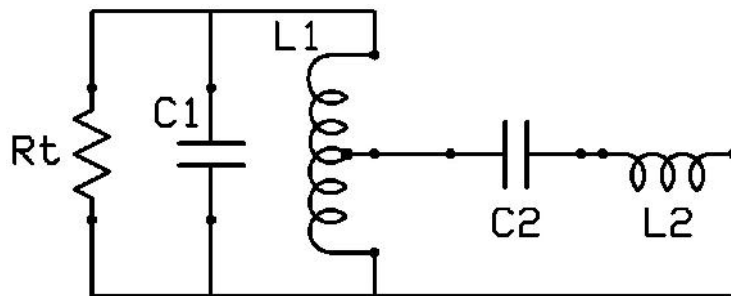


Figure 8. Impedance transformation within filter using tapped inductor.

The tap position on inductor L_1 determines the input impedance seen by resonator C_2 - L_2 . If L_1 is center tapped, i.e. a 2:1 turns ratio, then the input impedance seen by C_2 - L_2 will be R_t divided by 4.

This internal impedance transformation technique was used for the CW filter in my project.

Design Details

CW Filter

For the CW filter, a five-pole Butterworth bandpass response centered at 600 Hz was desired.

As shown in Figure 9, a spreadsheet was used to calculate the corresponding CW filter design data.

Center Frequency (Hz)	600					
Bandwidth (Hz)	232	232	232	232	232	232
Input Termination Impedance (ohms)	3					
Output Termination Impedance (ohms)	5					
AL	153	153	153	153	153	153
Length of One Turn (in)	1.8	1.8	1.8	1.8	1.8	1.8
Low Frequency (Hz)	484					
High Frequency (Hz)	716					
Geometric Mean Center Frequency (Hz)	588.679879	588.6798791	588.6798791	588.6798791	588.6798791	588.6798791
Normalized Lowpass Element Values	0.61803	1.61803	2	1.61803	0.61803	
Resonator Termination (ohms)	296	74	296	74	296	
Resonator Type	Parallel	Series	Parallel	Series	Parallel	
Capacitor (uF)	1.432353981	0.889880746	4.635224765	0.889880746	1.432353981	
Inductor (mH)	51.03078554	82.13926322	15.76927819	82.13926322	51.03078554	
Reactance (ohms)	188.7517327	303.8151989	58.32711669	303.8151989	188.7517327	
Number of Turns	578	733	321	733	578	
Wire Length (ft)	86.7	109.95	48.15	109.95	86.7	
Wire Resistance (ohms)	5.62683	7.135755	3.124935	7.135755	5.62683	
Inductor Q (best possible)	33.5	42.6	18.7	42.6	33.5	
External Winding Inductance (mH)	0.517203907				0.862006512	
External Winding Wire Resistance (ohms)	0.224				0.289	
Resonator:External Impedance Ratio	98.66666667				59.2	
Resonator:External Turns Ratio	9.933109617				7.694153625	
24AWG Resistance (ohms/ft)	0.02567	0.02567	0.02567	0.02567	0.02567	
28AWG Resistance (ohms/ft)	0.0649	0.0649	0.0649	0.0649	0.0649	

Figure 9. CW filter spreadsheet, design section.

For ease of use some spreadsheet conventions were adopted. All user-entered values have no colored background. Calculated results of interest to the user have a yellow background. Calculated or copied cells used internally by the spreadsheet have a blue background.

Since a Butterworth response was desired, the appropriate normalized lowpass filter element values were read from the Butterworth filter tables and entered into the spreadsheet.

The desired center frequency and bandwidth were entered into the appropriate fields.

The input and output termination impedances were entered. Many older receivers have 8-ohm output impedances. Conversely, modern receivers with internal feedback can have output impedances as low as a fraction of an ohm. Speaker impedances commonly range from 3.2 ohms to 8 ohms.

A value of 5 ohms was initially chosen as a nominal value for both input and output termination impedances, with the goal of having a single value that would provide acceptable results for all terminations likely to be encountered in practice.

Circuit simulation was used at a later time to evaluate filter performance for the expected ranges of receiver and speaker impedances. The simulation revealed an input termination impedance of 3 ohms was actually a better choice for overall performance, so that design change was made. This finding was true for both CW and voice filters.

The A_L and turn-length values from the telephone loading coil inductor measurements were entered into the spreadsheet.

An arbitrary initial set of resonator termination impedances was also entered.

The resulting design details were immediately displayed. This instant response made it extremely efficient to evaluate the results of any input design parameter changes.

The bandwidth and resonator termination values were then iterated to arrive at a design solution that maximized the inductor values, with the constraint that none of the inductor values exceeded the inductance of the pre-wound telephone loading coils.

Center-tapped parallel resonator inductors were chosen for this design as this allowed the series resonator inductor values to be reduced by a factor of four. Note the series resonator termination values entered by the user are one-fourth the values of the parallel resonator terminations.

Voice Filter

For the voice filter, a seven-pole 0.1-dB ripple Chebyshev bandpass response from 300 Hz to 3 kHz was desired.

As shown in Figure 10, a similar spreadsheet was used to calculate the corresponding voice filter design data.

Center-tapped inductors were not used in this design because the calculated component values did not indicate a significant advantage in doing so.

The low corner frequency was originally set to 300 Hz. After reviewing subsequent simulation data, it was shifted down to 260 Hz so there would be less loss at 300 Hz.

The resonator termination impedances were iterated in a similar manner as was done for the CW filter to arrive at preferred inductor values.

Low Frequency (Hz)	260						
High Frequency (Hz)	3000						
Input Termination Impedance (ohms)	3						
Output Termination Impedance (ohms)	5						
AL	153						
Length of One Turn (in)	1.8						
Bandwidth (Hz)	2/40						
Geometric Mean Center Frequency (Hz)	883.1760866	883.1760866	883.1760866	883.1760866	883.1760866	883.1760866	883.1760866
Normalized Lowpass Element Values	1.262	1.52	1.68	2.239	2.239	1.52	1.262
Resonator Termination (ohms)	182	182	182	182	182	182	182
Resonator Type	Parallel	Series	Series	Parallel	Parallel	Series	Parallel
Capacitor (uF)	0.40277073	2.02097752	1.82850347	0.714582936	0.714582936	2.02097752	0.40277073
Inductor (mH)	80.62848354	16.06885425	17.75031259	45.44580001	45.44580001	16.06885425	80.62848354
Reactance (ohms)	447.4198981	89.16855205	98.55471542	252.1857577	252.1857577	89.16855205	447.4198981
Number of Turns	726	324	341	545	545	324	726
Wire Length (ft)	108.9	48.6	51.15	81.75	81.75	48.6	108.9
Wire Resistance (ohms)	1.06/61	3.15414	3.319635	5.3055/5	5.3055/5	3.15414	1.06/61
Inductor Q (best possible)	63.3	28.3	29.7	47.5	47.5	28.3	63.3
External Winding Inductance (mH)	1.325040938						2.215068229
External Winding Wire Resistance (ohms)	0.359						0.463
Resonator:External Impedance Ratio	60.56666667						36.4
Resonator:External Turns Ratio	7.788880964						6.033241252
24AWG Resistance (ohms/ft)	0.02567	0.02567	0.02567	0.02567	0.02567	0.02567	0.02567
28AWG Resistance (ohms/ft)	0.0649	0.0649	0.0649	0.0649	0.0649	0.0649	0.0649

Figure 10. Voice filter spreadsheet, design section.

Spreadsheet Design Calculations

For the CW filter, the low and high corner frequencies are calculated by dividing the bandwidth in half and adding or subtracting that quantity to the center frequency.

For the voice filter, the corner frequencies are entered by the user and the calculated bandwidth is simply the difference between them

The geometric mean center frequency is especially important for subsequent calculations and resonator alignment. It is calculated from the low and high corner frequencies as follows:

$$F_c = (F_{\text{low}} * F_{\text{high}})^{1/2}$$

The resonator capacitor and inductor values are calculated by frequency- and impedance-scaling the lowpass filter element values according to the following formulas:

$$C_P = n / (2 * \pi * B * R)$$

$$L_P = (B * R) / (n^2 * \pi * F_c^2)$$

$$C_S = B / (n * 2 * \pi * R * F_c^2)$$

$$L_S = (n * R) / (2 * \pi * B)$$

where

C_P is the capacitor value (parallel-resonant branches only),

L_P is the inductor value (parallel-resonant branches only),

C_S is the capacitor value (series-resonant branches only),

L_S is the inductor value (series-resonant branches only),

n is the normalized lowpass filter element value for that branch,

B is the filter bandwidth, and

R is the termination impedance for the applicable branch.

The reactance value displayed is the resonator capacitive or inductive reactance at F_C . Each resonator is tuned to F_C , so the capacitive and inductive reactance values are equal in magnitude at that frequency:

$$|X| = 2 * \pi * F_C * L = 1 / (2 * \pi * F_C * C)$$

The number of turns needed is calculated as follows:

$$N = (L / A_L)^{1/2}$$

The total wire length is estimated by multiplying the wire length per turn by the number of turns needed.

The wire resistance is calculated by multiplying the wire length by the appropriate wire resistance per foot corresponding to the wire gauge.

The best-possible inductor Q is estimated by dividing the reactance of the inductor at F_C by the wire resistance. This Q calculation only considers losses due to the resistance of the wire and is therefore only a best-case estimate. Core losses, etc. are not considered. The inductive reactance is proportional to frequency; accordingly, so is the inductor Q within limits.

The input and output resonator inductors have additional windings for impedance matching to the source and load. These are referred to as external windings in the spreadsheet and in this document.

The external winding inductances are calculated by dividing the applicable resonator inductance by the desired resonator-to-external-termination impedance ratio.

To minimize resistive losses, 24 AWG wire was used for the lower-impedance external windings in lieu of 28 AWG wire. This larger-size wire has significantly lower resistance but is still relatively easy to manipulate.

The winding resistance of each external winding was estimated by dividing the applicable resonator's wire resistance by its turns ratio, and then scaling this value to account for the use of the larger 24 AWG wire.

Simulation

The candidate filter designs were simulated using LTSpice²².

For simulation purposes, all capacitors were considered to be ideal. Inductors were specified as having a series resistance equal to their estimated wire resistance. Coupled inductors were assumed to have unity coupling.

A screen shot of the simulation circuit used for the CW filter with a corresponding plot of the frequency response is shown in Figure 11.

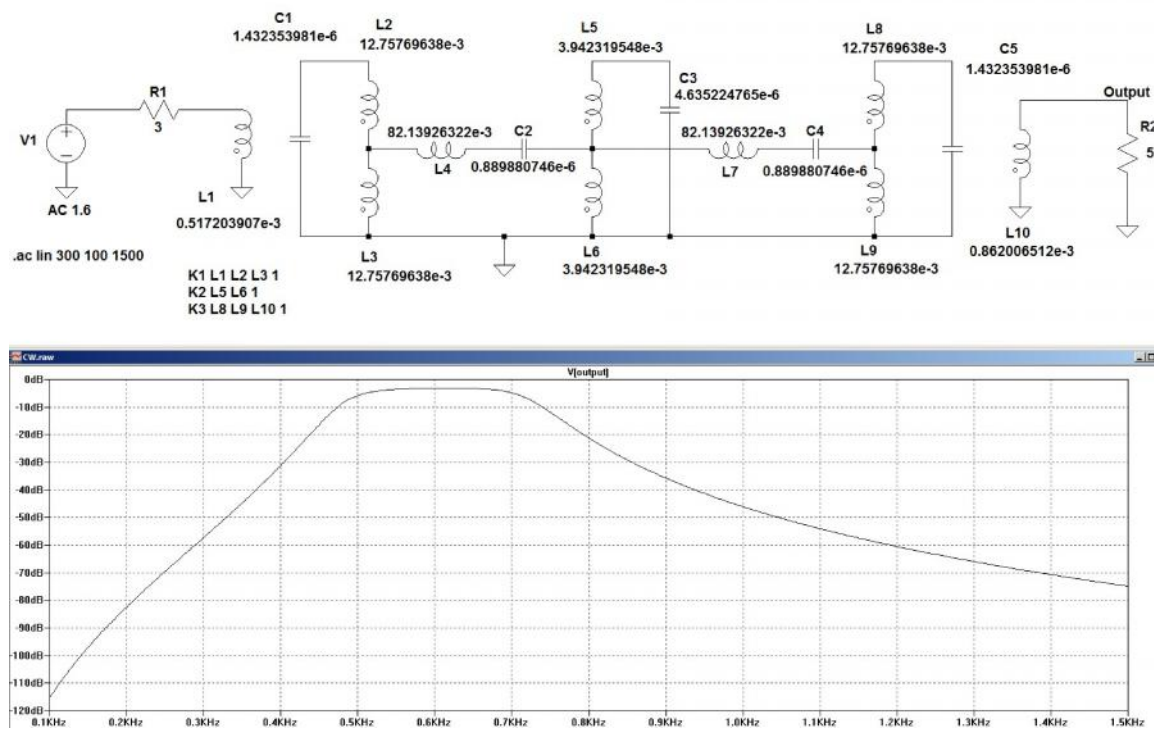


Figure 11. CW filter simulation screen shot.

Similarly, the voice filter was simulated as shown in Figure 12.

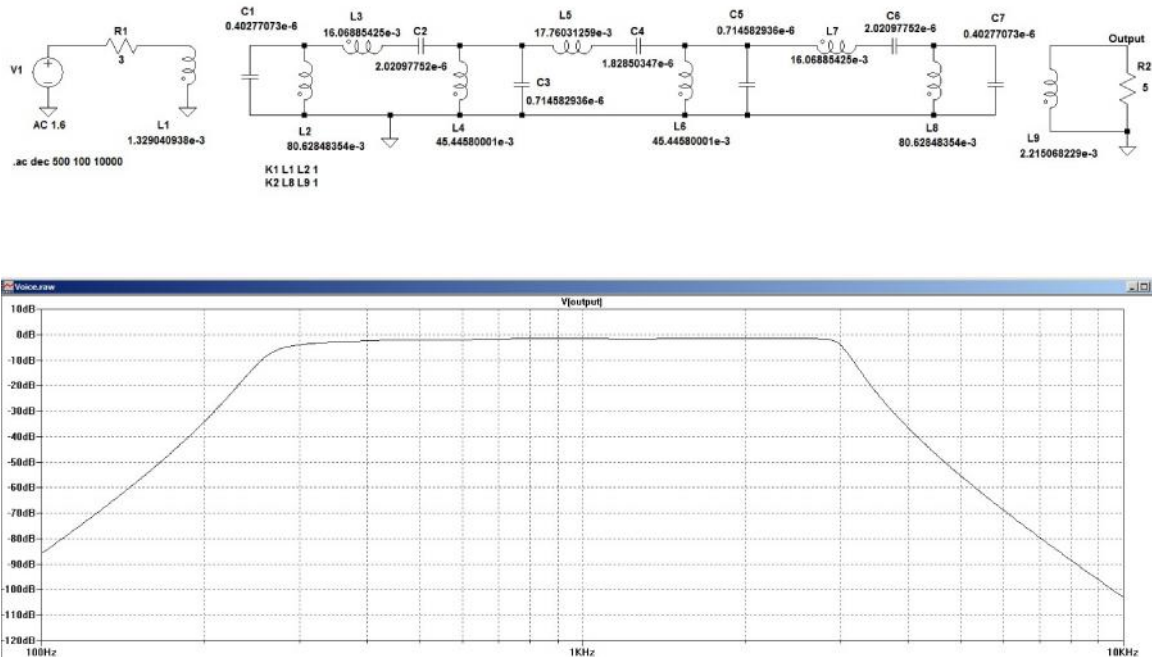


Figure 12. Voice filter simulation screen shot.

These simulation results were very encouraging, although they were obtained using perfectly matched source and load impedances.

Additional simulation runs were performed to assess the effects of mismatched source and load impedances.

One of the early findings was that insertion loss was noticeably higher with very low source impedances. This discovery led to more simulation runs to evaluate different input transformer turn ratios. From this work, an input transformer match to 3 ohms was found to be optimal for the expected ranges of external termination impedances. The filter designs were modified accordingly.

Final simulation results of interest are shown in Figure 13 through Figure 16.

Many combinations of source and load impedances could have been simulated but the intent was not to perform an exhaustive quantity of runs. Rather, the goal was to establish performance bounds for minimum and maximum termination impedances that could reasonably be expected in practice.

Therefore, the following five cases were simulated for each filter:

- 3-ohm source impedance, 5-ohm load impedance, black trace in plots. This is the reference for a perfectly matched filter and represents the ideal case.
- 0.3-ohm source impedance, 3.2-ohm load impedance, orange trace in plots.
- 0.3-ohm source impedance, 8-ohm load impedance, red trace in plots.
- 8-ohm source impedance, 3.2-ohm load impedance, green trace in plots.
- 8-ohm source impedance, 8-ohm load impedance, blue trace in plots.

For these simulation runs, the voltage source magnitudes were normalized so that if the filter was bypassed entirely then the output voltage at the load resistor would be 1 volt. In this manner, only the filter effects would be shown.

As shown in the plots, the out-of-band rejection was not significantly affected by the mismatched terminations. However, the mismatched terminations did cause varying levels of ripple within the passband. Insertion loss was also somewhat affected.

The most severe ripple was evident when the load impedance was 8 ohms. One potential mitigation strategy is to connect an additional resistor across the load to lower the impedance. This will reduce the ripple but at the expense of increased loss. If this additional load is actually another 8-ohm speaker, however, the extra loss is almost inconsequential due to the additional acoustic power.

Figure 17 shows the ripple reduction that can be obtained by adding an additional 8-ohm load in parallel to an existing 8-ohm load.

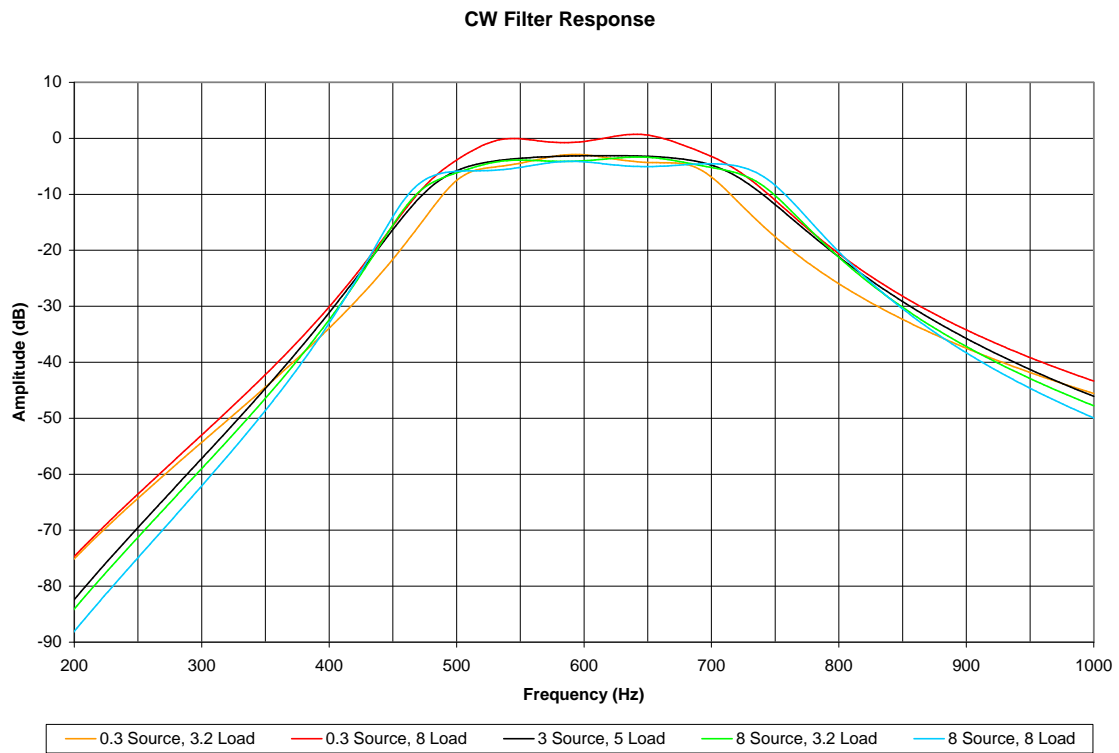


Figure 13. CW filter simulation with various termination impedances.

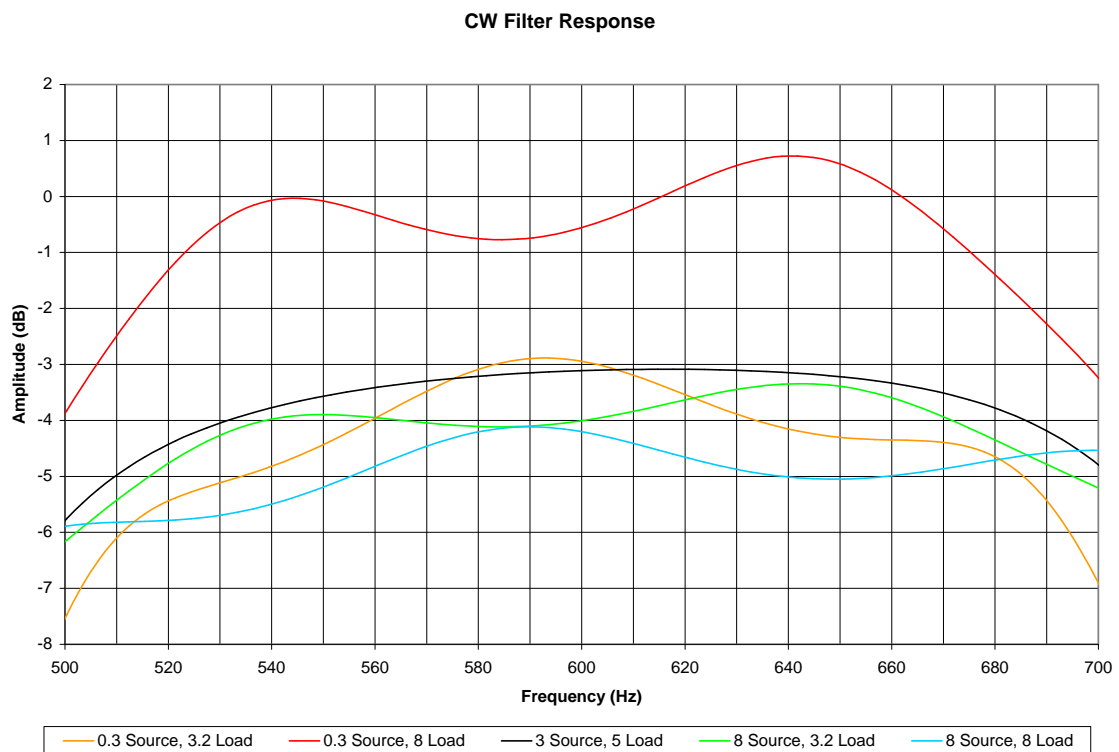


Figure 14. CW filter simulation with various termination impedances, zoomed in to passband.

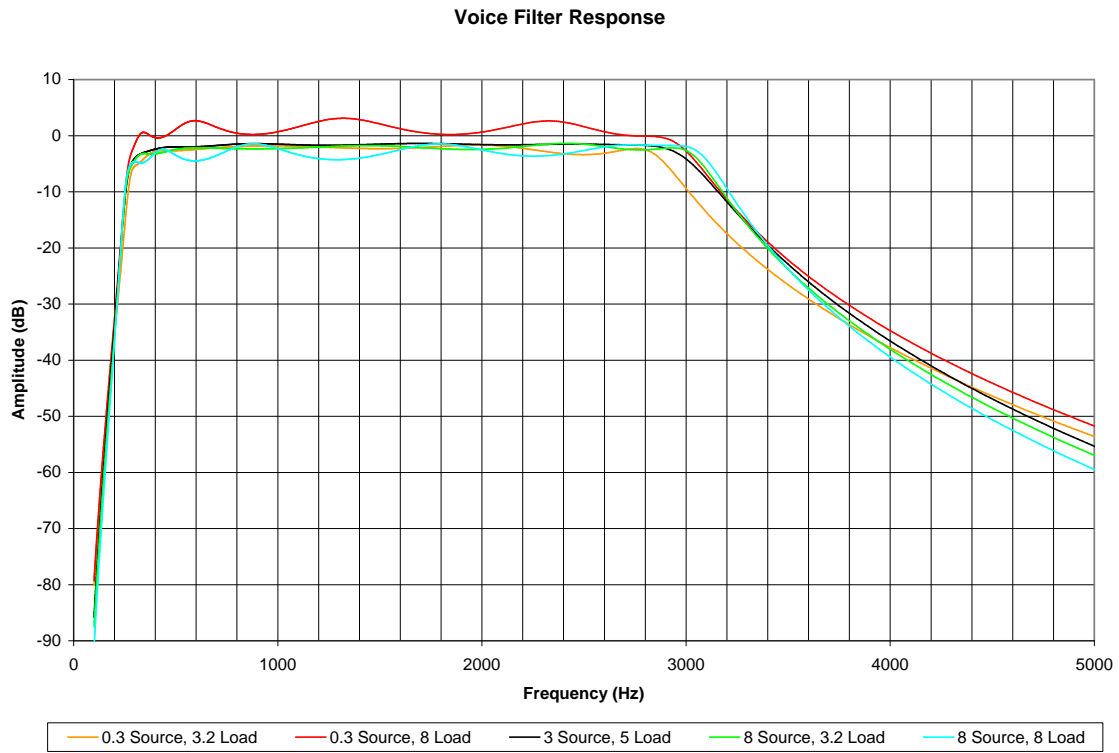


Figure 15. Voice filter simulation with various termination impedances.

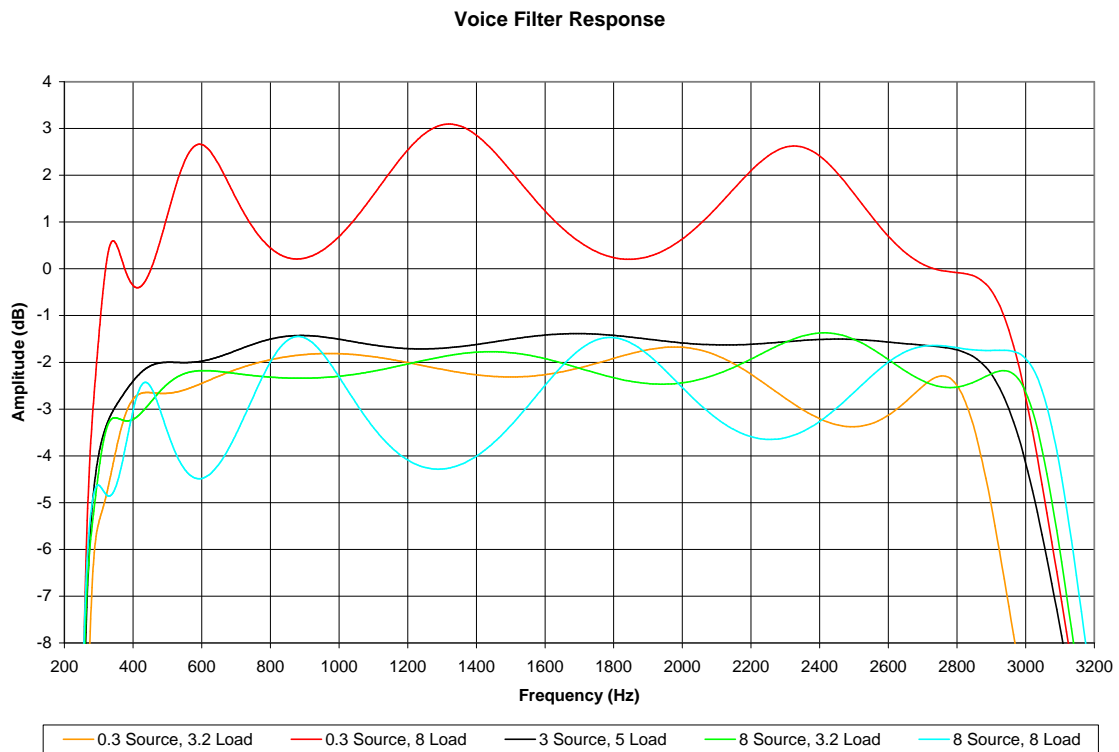


Figure 16. Voice filter simulation with various termination impedances, zoomed in to passband.

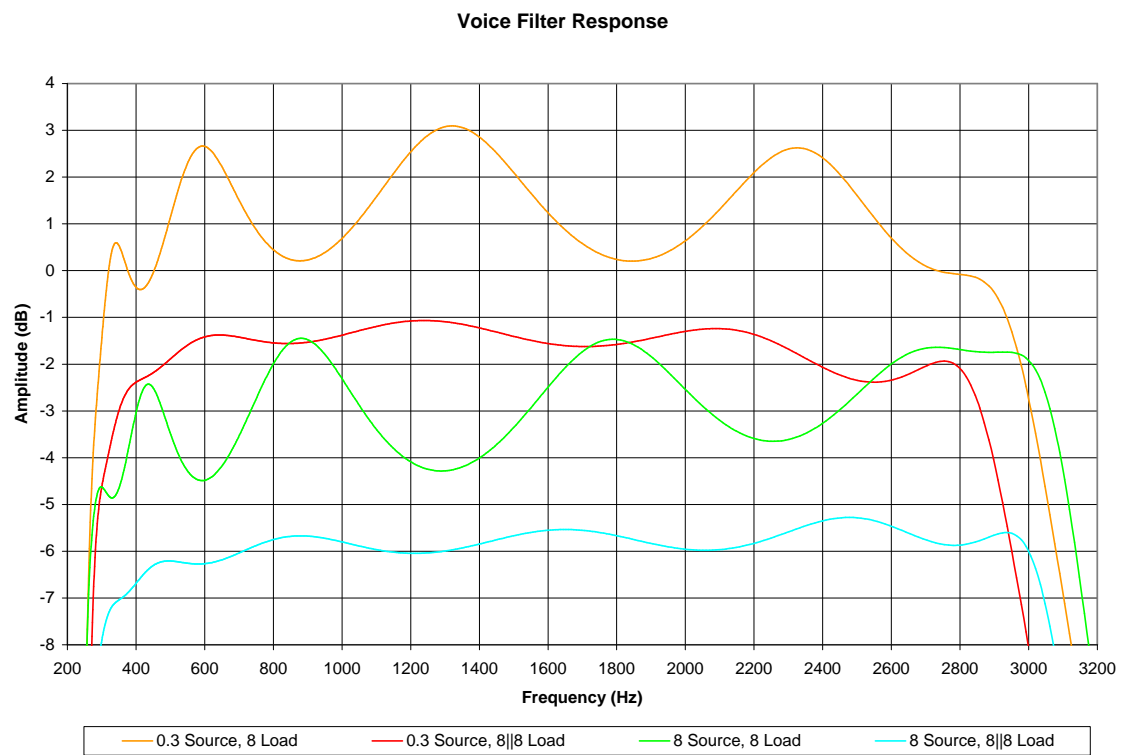


Figure 17. Voice filter simulation showing ripple reduction due to additional 8-ohm load.

Resonator Preparation

Winding Toroidal Cores

Manually winding a toroidal core that requires more than a few feet of wire can be quite a challenge. Use of a shuttle to hold the wire makes the task much easier.

Figure 18 shows a shuttle built for this purpose. It is nothing more than a 3/16-inch wooden dowel with a slot cut in each end. A small piece of electrical tape is included to prevent unraveling, although it is not really necessary. A Dremel tool equipped with a small circular saw blade was used to cut the slots in the dowel.

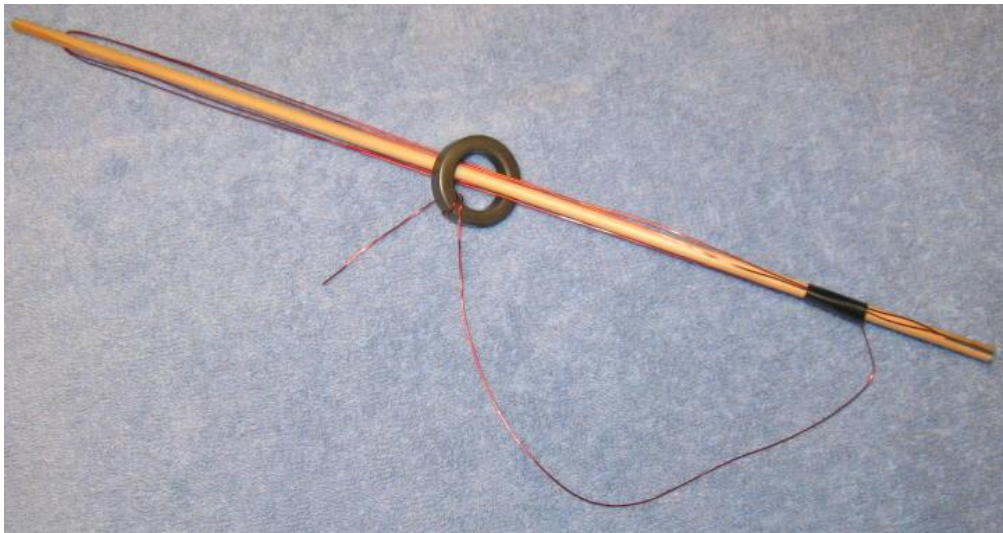


Figure 18. Shuttle used for winding toroidal cores.

Inductor Adjustment

Each inductor was adjusted by repeatedly removing turns and measuring the inductance using an LCR meter. This was done until the desired inductance was obtained.

To speed the process, a spreadsheet was used to estimate the number of turns needed as shown in Figure 19 and Figure 20. Each time one or more turns were removed, the current number of turns and the corresponding inductance measurement were entered. The spreadsheet then used this information to calculate an updated estimate of the final number of turns needed.

Once the desired inductance was obtained, the inductor DC resistance and Q at various frequencies were measured and recorded in the spreadsheet. These measurements were saved for informational purposes only and were not used for anything else.

Number of Resonator Turns Actual	579	728	313	727	580
Measured Resonator Inductance (mH)	51.082	82.17	15.796	82.224	51.077
Est. Final Number of Resonator Turns	579	728	313	727	580
Target Resonator Inductance (mH)	51.03078554	82.13926322	15.76927819	82.13926322	51.03078554
AL Calculated	152.3739638	155.0424164	161.2346763	155.5714067	151.834126
Measured Q at 400 Hz	20.6	26.2	11.8	26	21.3
Measured Q at 600 Hz	30.6	38.9	17.7	38.5	31.6
Measured Q at 800 Hz	40.4	50.9	23.5	50.4	41.6
Measured Resistance (ohms)	6.18	7.79	3.27	7.82	5.93

Figure 19. Spreadsheet used to adjust resonator inductors.

Number of External Turns Actual	58		75
Measured External Winding Inductance (mH)	0.513		0.873
Est. Final Number of External Turns	58		75
Target External Winding Inductance (mH)	0.517203907		0.862006512
AL Calculated	152.4970273		155.2
Measured Resistance (ohms)	0.242		0.291

Figure 20. Spreadsheet used to adjust external windings.

Resonator Tuning

Once the inductors were adjusted, the resonators were individually tuned using the test setup shown in Figure 21. All resonators were tuned using the same method regardless of their final connection in the filter as series- or parallel-resonant branches.

The tuning procedure was fairly simple. The function generator frequency was manually adjusted for a peak reading on the oscilloscope. This measured peak frequency is the resonant frequency of the LC network under test.

The capacitor shown in the figure is actually a parallel combination of several capacitors. Capacitors were selected as needed to set the resonant frequency of the network to the applicable filter's geometric mean center frequency F_C . From the spreadsheet calculations, $F_C = 589$ Hz for the CW filter and $F_C = 883$ Hz for the voice filter.

These same capacitors, now matched to the individual inductor, were used later to build the filter.

The two 47K resistors prevented loading of the LC network so that a sharp peak in the response could be observed.

All components were tack soldered during tuning to prevent erroneous results due to poor connections.

Using this setup it was possible to quickly tune all resonators to within a couple Hz of the desired F_C .

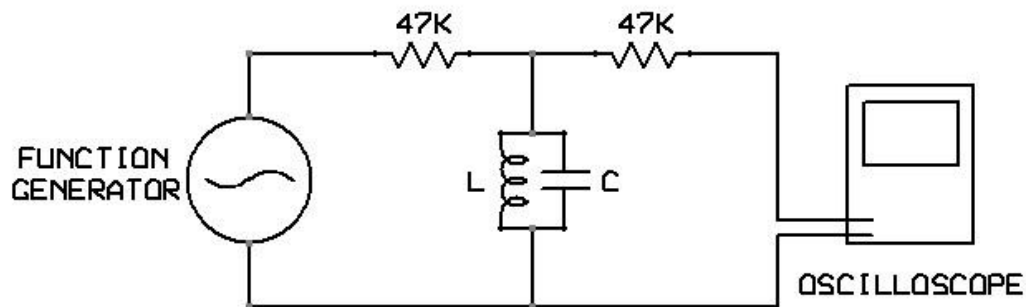


Figure 21. Test setup used for resonator tuning.

Schematic Diagram

A schematic diagram of the completed passive LC audio filter project is provided in Figure 22.

The input signal can be selected from any one of three sources to allow the filter to be shared among multiple receivers without swapping cables.

Both 1/4-inch and 3.5-mm headphone jacks are provided.

If stereo headphones are not used, the headphones must at least be wired with a stereo connector.

It is possible to have both the external speaker and the headphones on at the same time.

If the external speaker is switched off, the filter output is terminated with three 15-ohm resistors in parallel. This was done because many headphones have high impedances.

A switch is included so the filter can be easily bypassed when not desired.

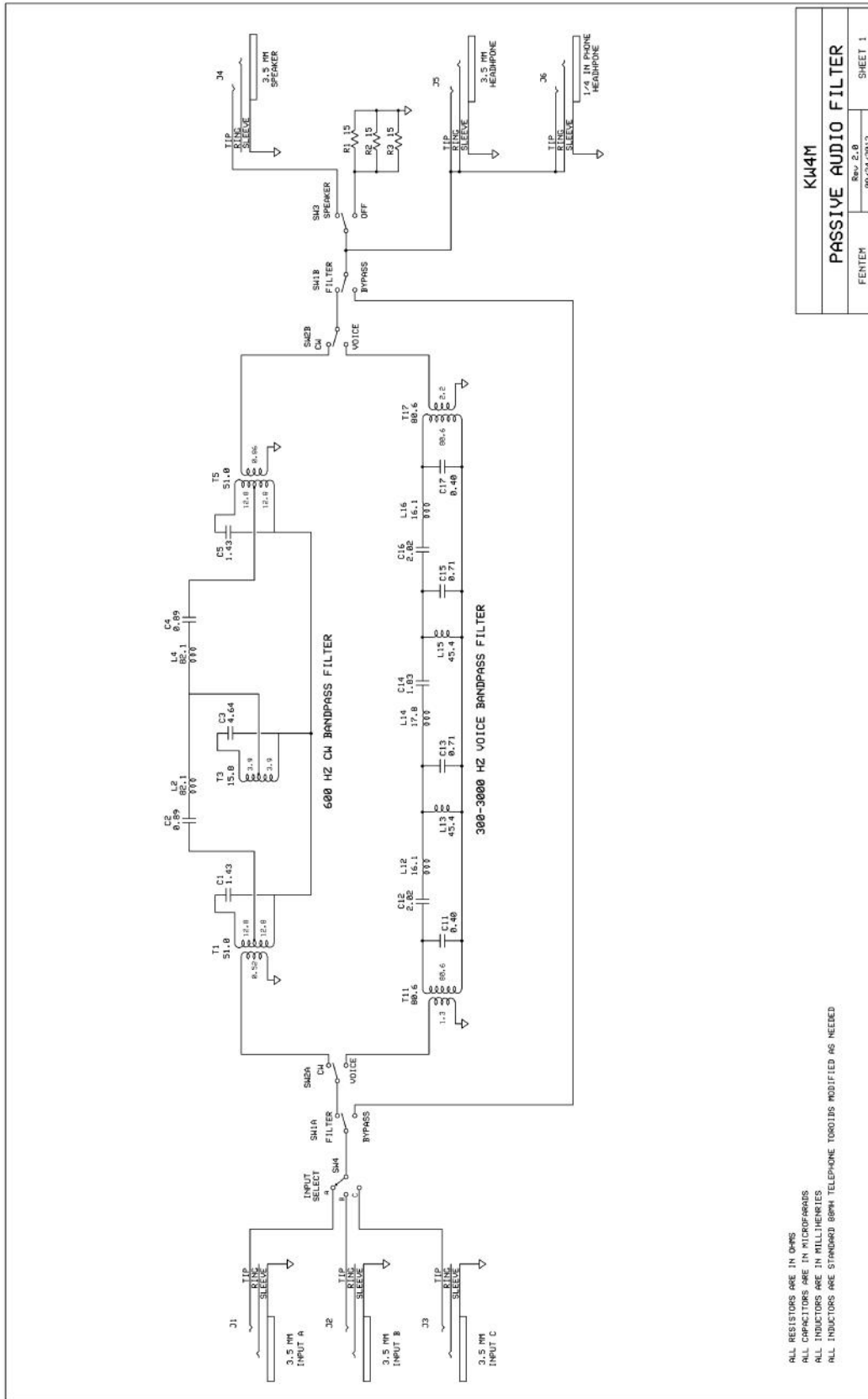


Figure 22. Schematic diagram.

Testing

After assembly, the frequency response characteristics of the CW and voice filters were measured and compared with the predicted results as shown in Figure 23 through Figure 26. These measurements were performed with resistive source and load terminations of 3 ohms and 5 ohms, respectively.

The measured filter results closely tracked the predicted results.

For those readers who wish to perform similar testing, the capabilities of the test equipment must be considered. The harmonic distortion performance of the signal source is especially important, particularly if the apparatus used to measure the signal level at the filter output is untuned.

For example, if the signal source is set to 300 Hz then its second harmonic would be at 600 Hz, the center of the filter passband. An untuned signal detector on the filter output would not be able to discriminate between the second harmonic and the greatly-attenuated fundamental signal. This could lead to an erroneous conclusion that the filter attenuation at 300 Hz is much worse than is actually the case.

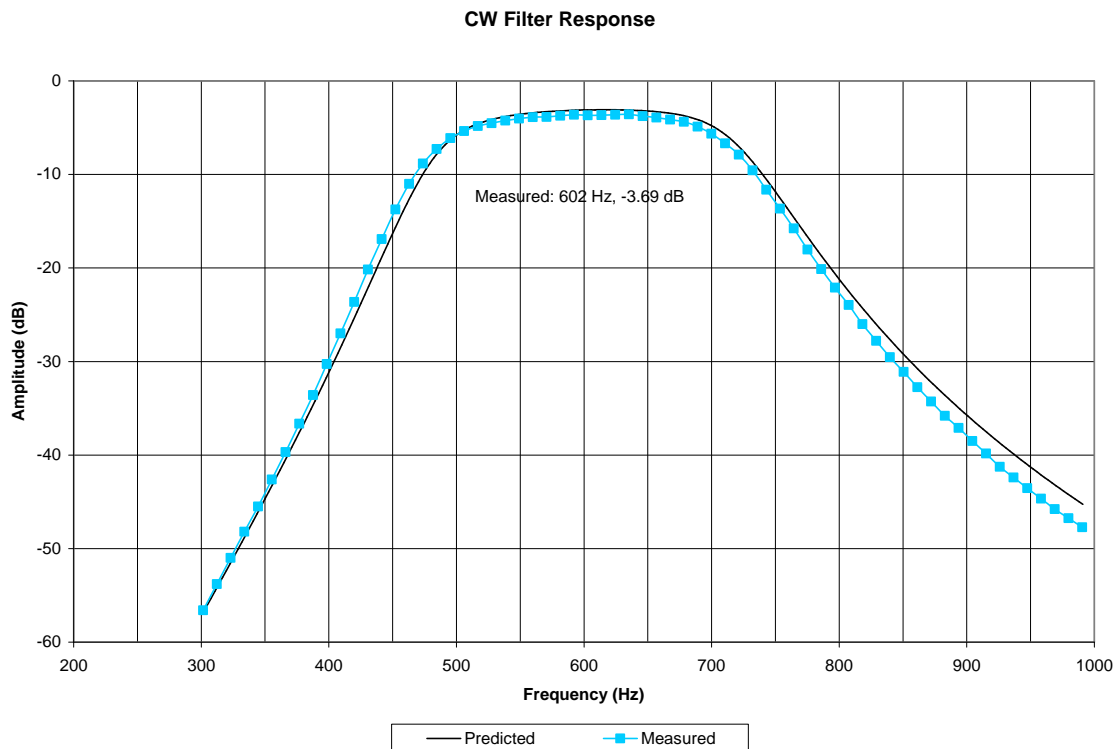


Figure 23. Predicted and measured CW filter frequency responses.

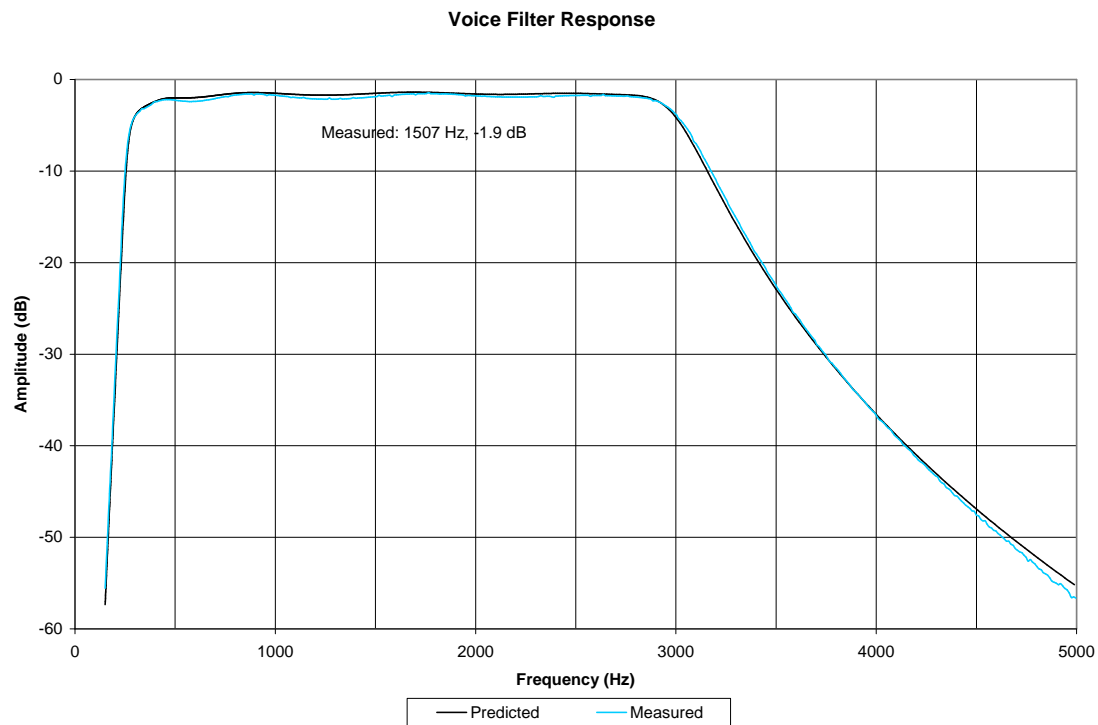


Figure 24. Predicted and measured voice filter frequency responses.

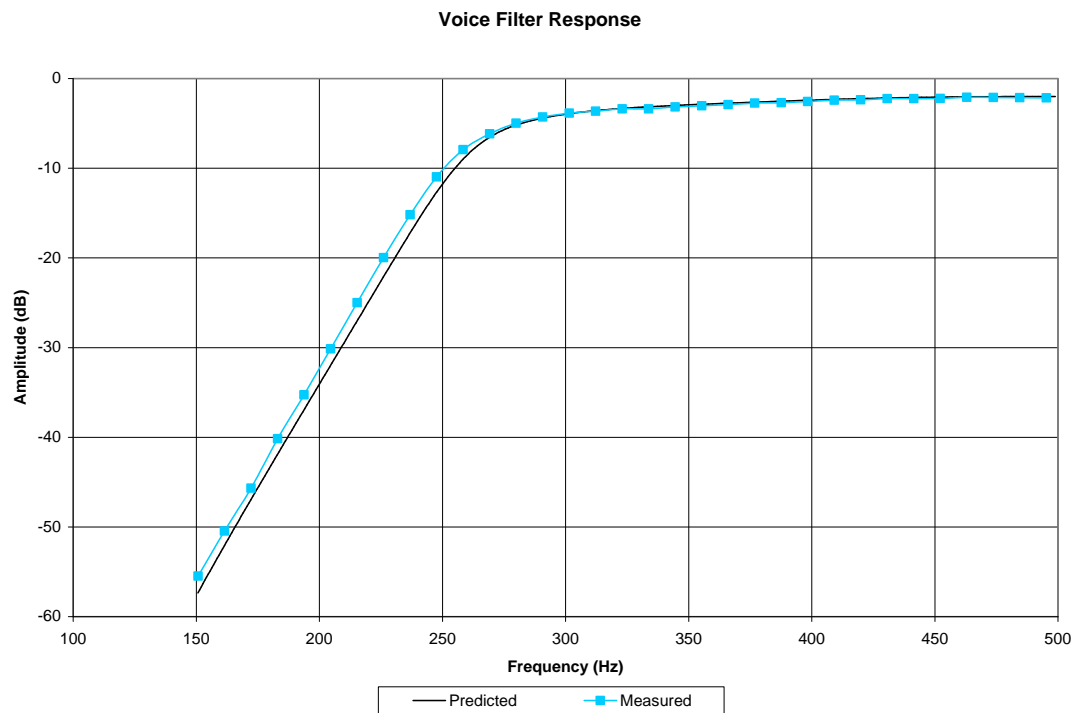


Figure 25. Predicted and measured voice filter frequency responses, zoomed to lower corner.

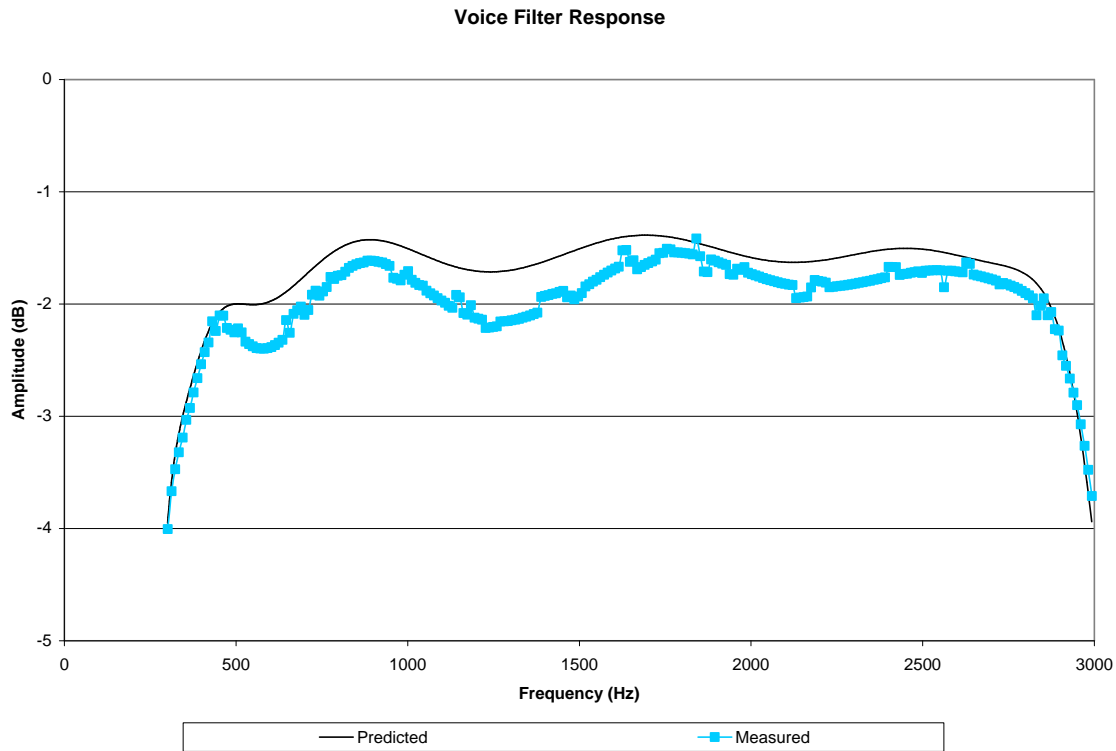


Figure 26. Predicted and measured voice filter frequency responses, zoomed to passband.

These measurements showed the filters performed as desired for matched source and load termination impedances.

Modern amateur radio receivers generally have very low output impedances as their output stages typically utilize integrated circuits with feedback.

An audio amplifier with a TDA2003A integrated circuit was used to simulate a typical modern receiver output stage for lab testing. The output impedance of this amplifier was measured and found to range from 0.6 ohms at 300 Hz down to 0.1 ohms at 3 kHz.

The frequency response curves of the CW and voice filters were again measured while using this amplifier to drive the filter. The results are shown in Figure 27 and Figure 28.

It was concluded from these measurements that the filters should perform well in practice.

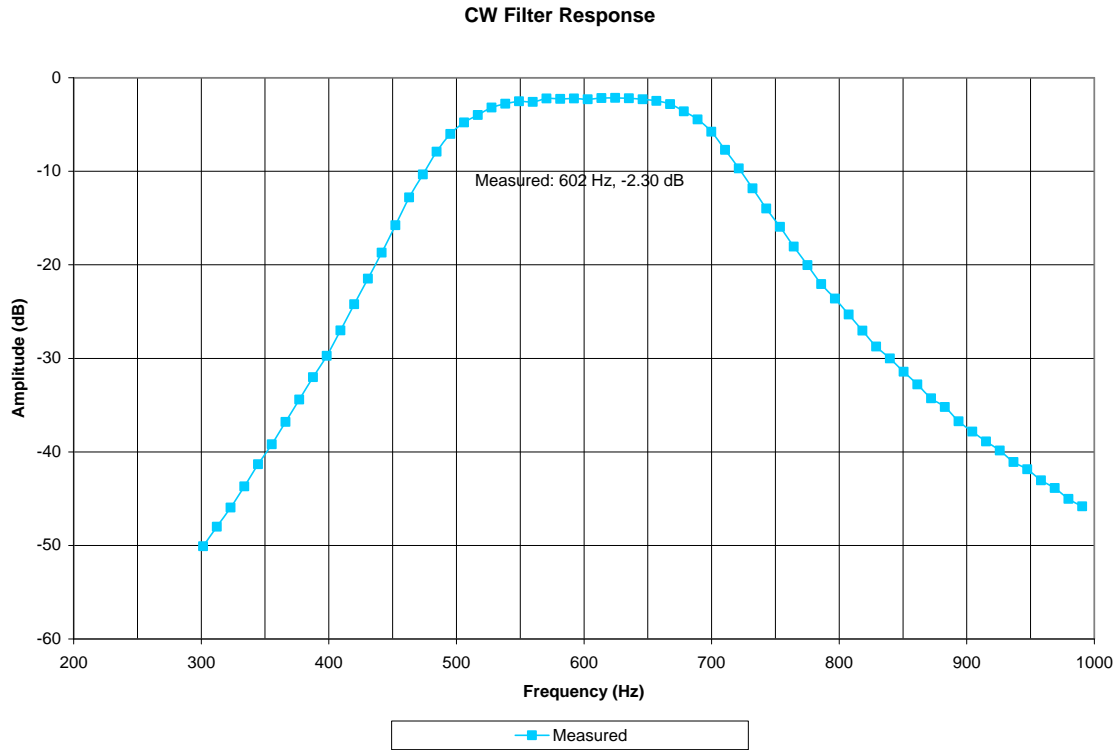


Figure 27. CW filter frequency response, TDA2003A source and 5 ohm load.

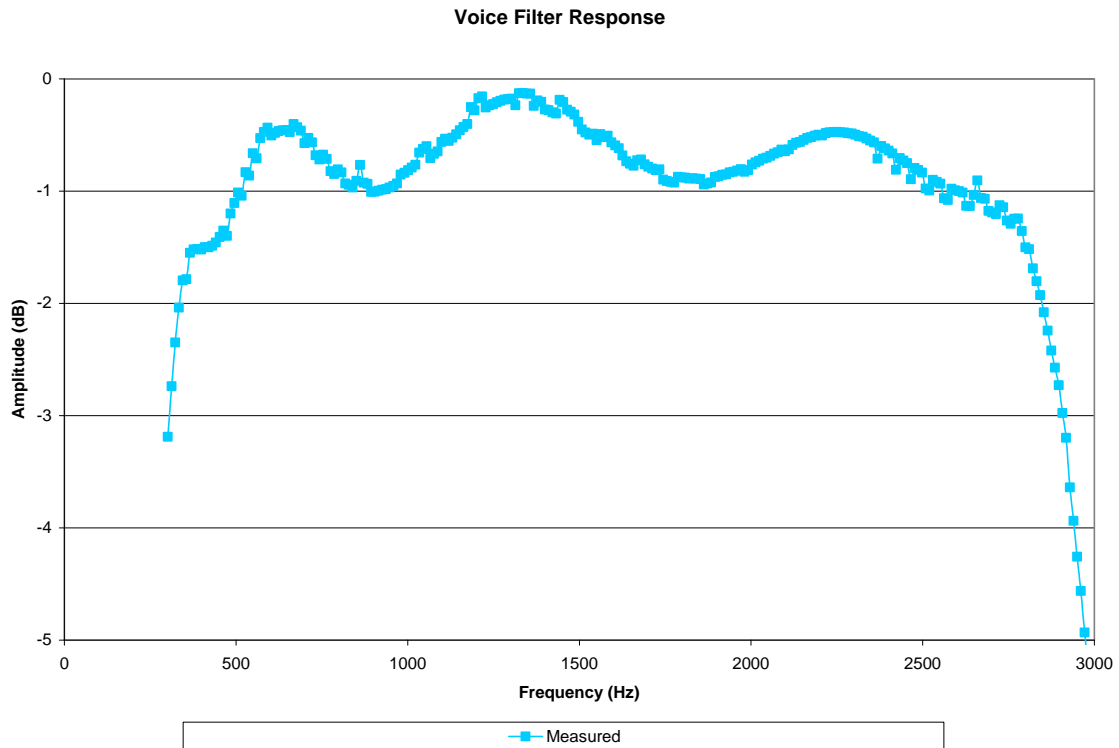


Figure 28. Voice filter frequency response in passband, TDA2003A source and 5 ohm load.

Software and Data Files

Software Used in this Project

Microsoft Excel was used to prepare and utilize the design spreadsheet, and to format and generate plots of predicted and measured frequency response data.

LTSpice IV²² from Linear Technology was used to simulate the filter designs.

Visual Analyser 2011²³ from SillanumSoft was used to measure and record frequency response data.

Elsie

Another software product of potential interest is Elsie²⁴ from Tonne Software. Elsie is a very capable filter design and analysis application. It includes several advanced features such as Monte Carlo analysis for use in evaluating a filter design for production variations, a rich set of filter topologies and families, as well as support for a multitude of plot types.

The student version is available as a free download but it only supports seven “stages” of components. This was adequate for simulation of the voice filter, but not for the CW filter with its tapped inductors. The Pro version does not have this limitation.

Tapped inductors are not explicitly included as components. However, a transformer component is available that may possibly be used for this function. This option was not evaluated as including the transformers exceeded the limitations of the student version.

Inductors and capacitors can only be specified with a single Q value, and it is not frequency dependent. This may be acceptable for a narrowband RF filter but in my opinion this is lacking in fidelity for simulations over a wide frequency range.

Nevertheless, the application is very easy to use and may be appealing to some users as an alternate design and analysis tool.

Data Files

The spreadsheet design file, LTSpice schematic files, and the latest version of this document can be downloaded from the project web page²⁵. Readers are encouraged to experiment with these designs and to develop designs of their own.

Conclusion

The completed passive filter unit has only been in service at my home station for a relatively short time. But sufficient operating experience has been accumulated to provide an assessment of its utility.

When either filter is engaged there is no trace of residual power supply hum. Further, undesired receiver artifacts such as hiss and digital background noise are noticeably attenuated.

The passive filter adds no observable distortion or noise, unlike filters with active components that have been previously used at my station.

With the CW filter engaged, CW is more pleasant to copy and signals do indeed seem to pop up out of the noise. The improvement is especially evident with weak signals near the noise floor. The observed CW filter performance is consistent with the many outstanding online reviews.

With its wider bandwidth, the voice filter does not provide the same perceived dramatic improvement. However, it does improve intelligibility somewhat under crowded band conditions such as during a major contest. It could provide the extra edge needed to make a contact under certain conditions.

A perceived reduction in fidelity is a natural result of the loss of frequencies below 300 Hz. Therefore, it is usually preferable to bypass the voice filter during uncongested band conditions, particularly when signals of interest are strong.

The passive filter unit has met or exceeded my expectations. It is a worthy enhancement to my home station and is expected to remain in service for a long time.

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