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An Improved Audio-Frequency Bandpass Filter for Morse Code Reception

A look into the filter design rationale that explains why receivers with "rounded top" selectivity curves sound better to the CW operator, no matter how that selectivity is achieved.

In April of 2013 I proposed to Ed Wetherhold, W3NQN, that an unusual design should be used for an audio-frequency band-pass filter for Morse Code ("CW") reception. The filter was to be added on to the output of receivers used for CW work. Over the years, Ed had accumulated a number of toroidal inductors with a nominal 77 mH value and was using these inductors for building audio-frequency band-pass filters. Hence his well-known *nom de plume* "Filter Builder" in the Amateur Radio fraternity. I suggested to him a passive filter design, which used only one value of inductor. It was tailor-made to use some of Ed's stash of 77 mH inductors. Ed thought the design had merit and built several, and put them out into the field for testing. Feedback revealed the concept was quite satisfactory.

This article examines the CW filter design rationale, and explains why receivers with "rounded top" selectivity curves sound better to the CW operator, no matter how that selectivity is achieved.

The Problem

The IF response of the receiver used by a typical CW operator has a flat top with a width of typically 400 Hz. Figure 1 illustrates such an IF response. We have set the filter center frequency to 500 Hz for our tests. The filter bandwidth extends from 300 Hz to 700 Hz and drops off rather sharply beyond those limits. We are looking here at the response down at audio, not at the IF itself. Now we will apply a single CW "dit", a burst, into that IF and see what exits. We can expect it to be distorted — and to sound distorted as well. In fact, it appears as shown in Figure 2.

Such a signal corresponds to a 24 WPM Morse signal, typical of CW operators. The signal can be seen to be somewhat distorted at the leading and trailing edges. Time-domain analysis is being done here by *Elsie*, the filter design and analysis program.[1] *Elsie* also has

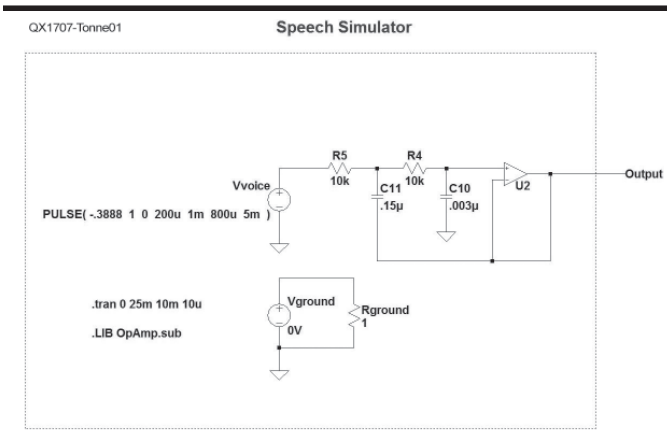

Figure 1 — Response of typical IF strip.

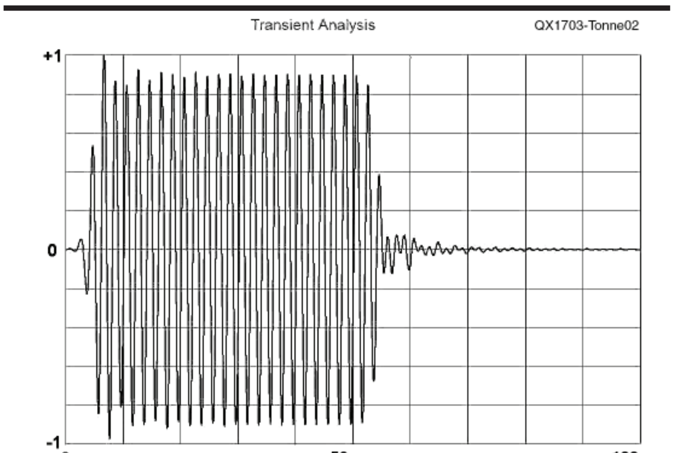

Figure 2 — A test pulse as it exits from that IF viewed at audio.

a very useful option of revealing the *envelope* of that time-domain waveform. Using this option reveals the distortion more clearly.

Figure 3 shows the envelope of this burst. The clearly visible ringing seen in this graphic forecasts an audibly obnoxious sound, the kind of sound CW operators find objectionable. This distortion is caused in large part by the group (envelope) delay distortion resulting from the sharp cutoff at the IF filter band edges. Group delay distortion is a common byproduct seen in a filter with a sharp band edge. Group delay equalization can reduce these effects to a limited extent. Figure 4 shows the amplitude response (top trace, left scale), and the group delay (lower trace, right scale) of the same IF filter.

Consider the keyed CW signal as a modulated wave. As we go out from "carrier" (500 Hz in this discussion), the "sidebands" go down uniformly in amplitude. But if they are not handled correctly in both time and amplitude, the signal will not sound pleasing. If some of those sidebands happen to be delayed more than they should we will have ringing. This is what we see in Figures 2 and 3.

The ringing gets worse as the CW speed increases to 30 or 35 WPM. If we can't change the shape of that filter response then we'll have to do something else to improve the sound quality.

A Solution

One way to improve the situation is to modify the *system* response by adding a second filter to the system at the receiver output. This "add-on" filter would have a somewhat rounded top and it would be noticeably narrower than the usual IF bandwidth. The responses of this add-on filter are shown in Figure 5, where the upper trace is amplitude and the lower trace is group delay.

This add-on filter is narrower than the IF strip and has a more gentle response in both magnitude and time. The system magnitude responses with (solid line) and without (dashed line) the add-on filter are shown in Figure 6.

The added audio band-pass filter adds some selectivity to the receiver. When we have added the new filter to the receiver we have narrowed the system bandwidth, but we've also rounded the top of the response. The impact of the rounded top on signal response at band-edges as can be seen in Figure 7. That pair of plots shows the system magnitude response (the upper plot) and group delay (the lower plot). The group delay of the sidebands at the band edges is significant, but notice that the add-on filter has reduced the magnitude of the sideband components at band edge to a very low amplitude. As a result, group delay problems at those frequencies are of much less consequence. We can expect the behavior of the system to be improved over the behavior of the receiver IF filter alone.

Passing the "dit" burst through the system now results in an output as shown in Figure 8. Compare this with Figure 3. The burst waveform shape is obviously improved. Reports from the units

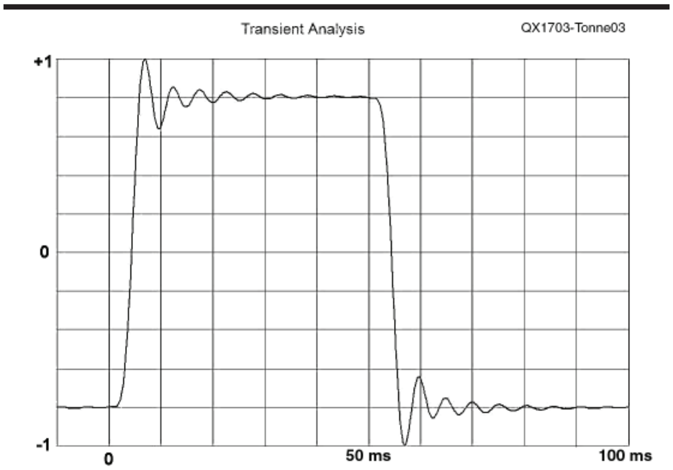

Figure 3 — The envelope of the burst shown in Figure 2.

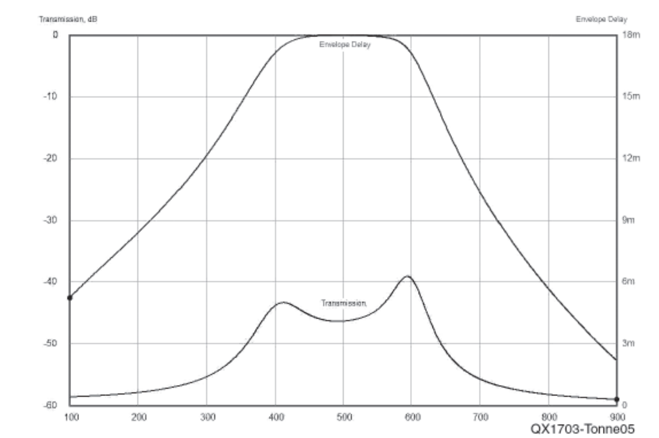

Figure 5 — Magnitude response of the add-on filter (upper plot) and group delay (lower plot).

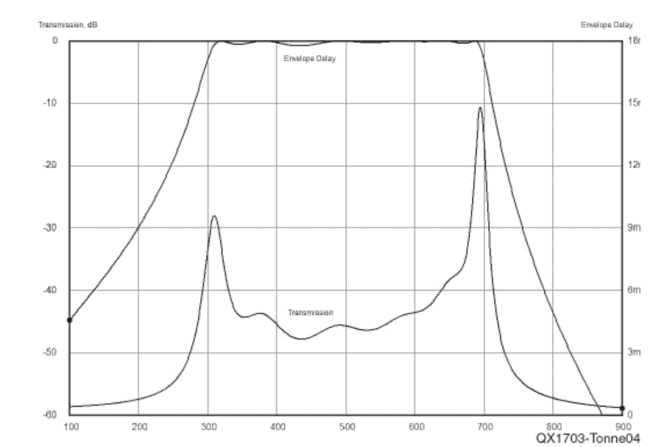

Figure 4 — Magnitude response of the receiver IF strip (upper plot) and the associated group delay (lower plot).

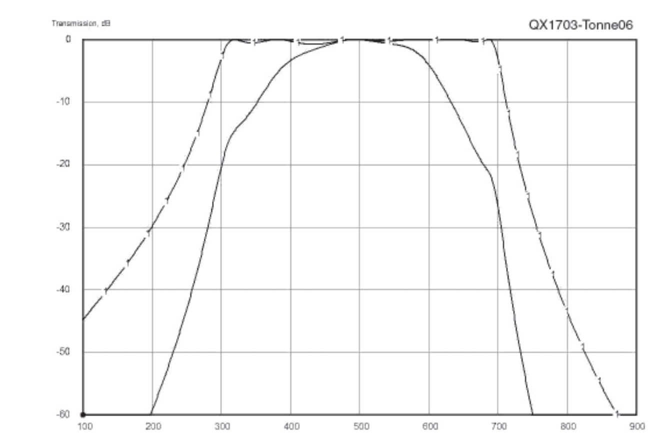

Figure 6 — The original receiver magnitude response (upper plot) and overall magnitude response with the add-on filter (lower plot).

delivered to the field consistently report that a CW signal passing through this filter sounds better than does a signal from the receiver IF alone — our expected result.

The add-on filter effectively masked the overshoot problem caused by the flat-topped IF filter in the receiver. This is because the add-on filter has removed the band edge components that would have caused the overshoots in a controlled manner. Another feedback item we see from the field is the reduction of noise when this filter is switched into the system. Let's see why this might be.

When the filter is analyzed using *Elsie* we see that the noise bandwidth of the filter is somewhat under 200 Hz (close to the 3 dB bandwidth displayed in Figure 5) using the analysis of Figure 9. Because the add-on filter is narrower in bandwidth than the receiver IF bandwidth, it determines the system noise bandwidth. Recall that the receiver IF noise bandwidth (Figure 1) is about 400 Hz.

Waveforms and Spectra

The pulse waveform used for this article has envelope rise and fall times of zero. The behavior of the system does not change until those times are increased to greater than about 1 ms. An interesting observation was made during the data-gathering portion of this research. The recommended rise and fall time of 5 ms in the transmitted signal essentially negates the need for the filter such as the one under discussion. The next set of graphics illustrates this point using the *LTspice* analysis tool.[2]

Figure 10 shows the raw keyed CW signal applied to the filter with envelope rise and fall times set to zero. The spectrum of this signal is shown in Figure 11. The sidebands extend outward symmetrically and slowly drop off in amplitude. This situation results in "key clicks". Applying a 5 ms rise time and fall time to the envelope of the

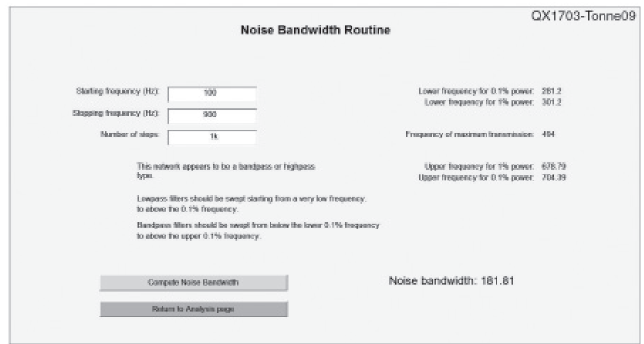

Figure 9 — Noise bandwidth analysis capability in *Elsie* software.

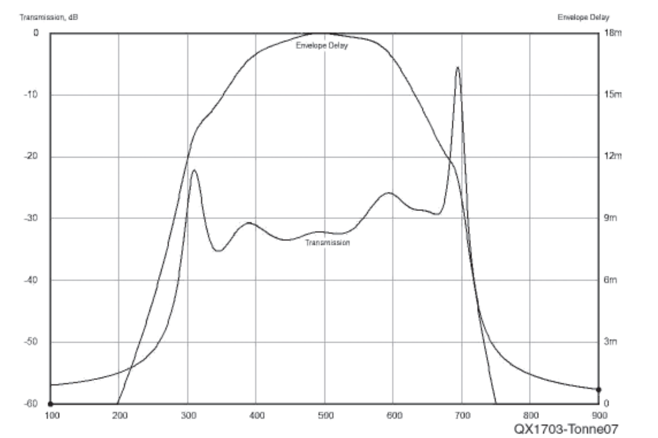

Figure 7 — Magnitude response of the overall system with the add-on filter (upper plot) and system group delay (lower plot).

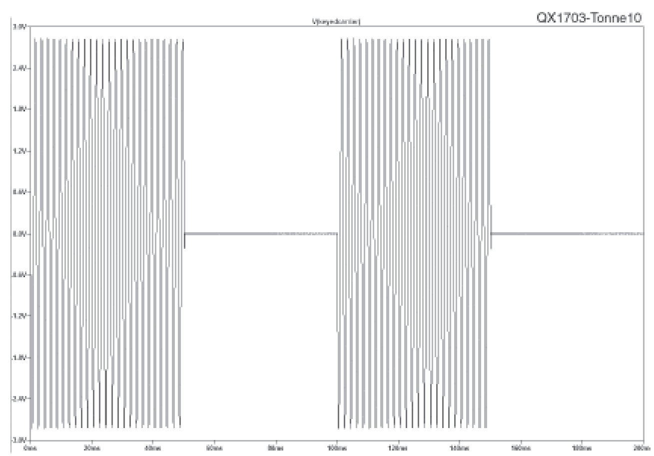

Figure 10 — Excitation waveform applied to the add-on filter.

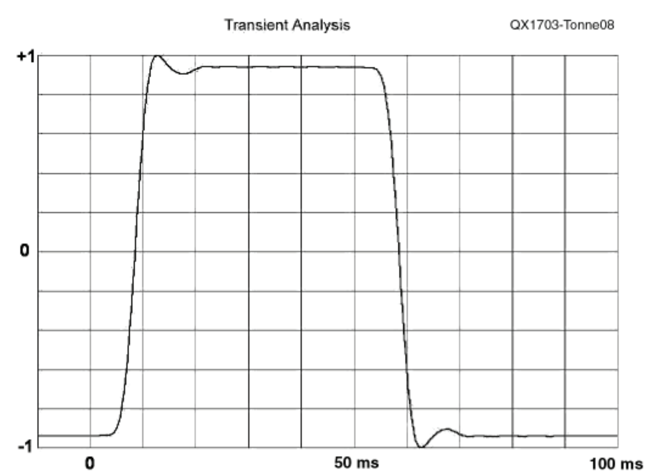

Figure 8 — The envelope of the burst when the add-on filter is used.

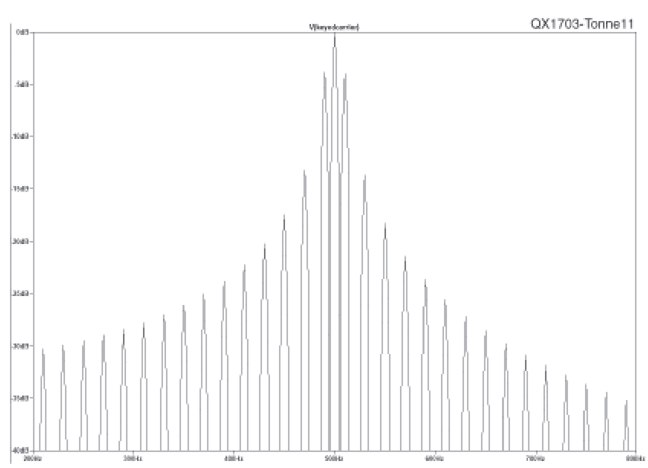

Figure 11 – The spectrum of s raw (unshaped) keyed CW signal.

pulse results in the response shown in Figure 12. The signal has a narrower bandwidth as can be seen in Figure 13. The signal occupies a noticeably narrower bandwidth, as compared with the spectrum in Figure 11. Passing this transmitted signal through our narrowband add-on filter should not result in significant alteration because the signal has already been made narrowband.

The rise and fall times were controlled by using a single-pole low pass (an RC network) filter with a rise time to 90% of 5 ms. Now we'll apply that narrowband signal (shown in Figure 12) to our add-on band-pass filter, to get the response seen in Figure 14. The difference between the waveforms of Figure 12 and Figure 14 is small and we see little ringing. Ringing causes the harsh sound that is objectionable to the CW operator.

The transmitted signal, narrow banded by controlling the rise and fall times of the envelope, is hardly altered in wave shape when additionally passed through the add-on filter. Bandwidth limiting of a transmitted CW signal is further discussed in the *ARRL Handbook*.[3]

I did not include the effects of the receiver IF filter for the *LTspice* analyses because the add-on filter band width is smaller than the IF bandwidth. The IF filter effect would be slight.

An Equivalent Active Filter

During the data-gathering portion of this paper, some correspondents asked about an active filter equivalent. Active band-pass filters are generally symmetrical on a geometric basis. Rephrased, they attenuate a given amount when the test frequency is changed by a given *factor* rather than by a specified frequency *shift*. As a simplistic example, the attenuation of the filter is typically the same when the test frequency is an octave below or an octave above the center frequency. When their responses are plotted on a linear frequency scale it can be seen that they commonly have poor attenuation on the high side of center.

A correctly behaving active filter design, that is to say one that attenuates about the same on both sides of the center frequency, has its response shown by the dotted points in Figure 15. The solid line in Figure 15 shows the response of our passive filter. The bandwidth of the active filter has been adjusted to be about the same as the field-proven passive filter. The top is somewhat narrower, and is more rounded. This active version has not yet been field tested. The output of this active filter subjected to our test burst is shown in Figure 16. This active filter is shown schematically in Figure 17.

Note that we have two multiple-feedback band-pass filter sections and three low-pass

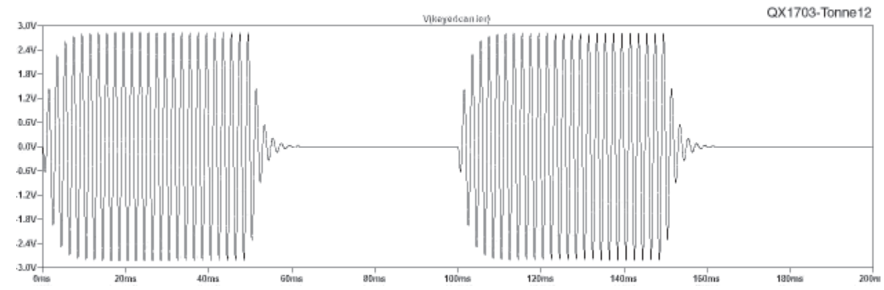

Figure 12 — The narrow banded pulse. The pulse was subjected to a 5 ms rise and fall time.

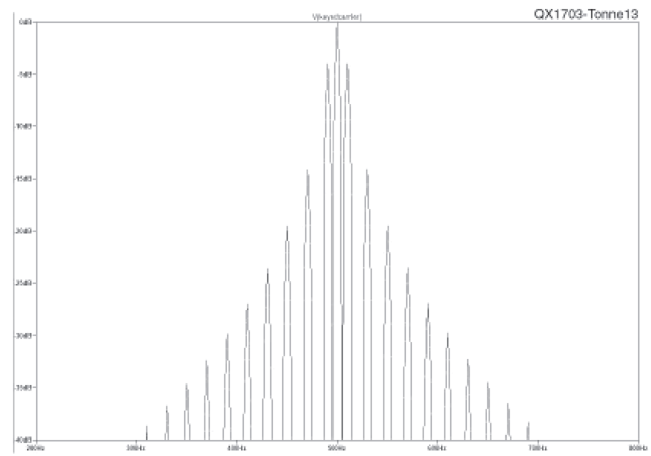

Figure 13 — Spectrum of the pulse when shaped by the 5 ms rise and fall time constraint.

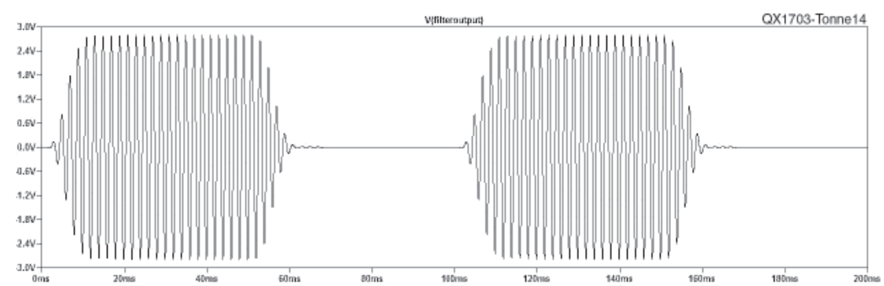

Figure 14 — The narrow band pulse of Figure 12 after it has passed through the add-on band-pass filter.

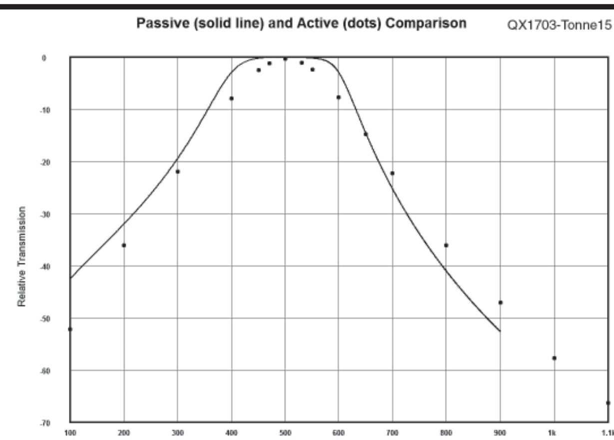

Figure 15 — Responses of the passive version of the filter (solid line) and an active filter approximation (dots) using a linear frequency scale.

filter sections. This complexity is required to achieve the transmission shown by the dots in Figure 15. This active filter has a modest gain at its center frequency of 500 Hz. It is noticeably more complex than the passive filter seen schematically in Figure 18. Furthermore it requires power, although physically it is more compact.

The Passive Filter Schematic

Figure 18 shows the schematic for the passive filter with a center frequency of about 500 Hz. and shows optional input and output matching transformers. Exact component values were computed to use 77.5 mH inductors. All of the inductors are of the same specified value — an attractive feature of the design. A practical filter could use 5% tolerance component values, although tighter tolerances would be preferred. This design closely exhibits arithmetic symmetry about the center frequency.

The passive filter is to be driven from, and terminated in, impedances of about 125 Ω. Transformers are shown on the input and output for matching from an 8 Ω source and to an 8 Ω load. Be aware that the transformers can cause distortions and can cause false responses to appear. If driven into saturation, some degree of nonlinearity can result, and the transformer can have a non-linear frequency response.

Final Comments

The passive design topology is mesh-capacitor coupled. All inductors are of the same value. The response has arithmetic symmetry. That is, the responses on either side of the center frequency are treated equally. This filter is from the Butterworth family, hence has a smooth top in the passband and a smooth descent into the stop bands.

The inductor Q values are somewhat low, about 40. This, too, contributes to a smooth, rounded pass band and a smooth descent into the stop band. Those filter attributes work together in a filter that has garnered numerous favorable reviews on eham.net.[4] Ed Wetherhold has offered to supply components for this filter.[5]

James L. Tonne holds the Amateur Extra class call sign W4ENE, and was first licensed in 1951. His current Amateur Radio interests are largely focused on speech processing and filter design. He has written several articles for QST and QEX and was a major contributor to the RF and Filters chapter in the ARRL Handbook. He is the author of the Tonne Software package on the CD accompanying the ARRL Handbook and included as part of the downloadable package available on the ARRL website.

Notes

[1]Free student edition, **www.arrl.org/arrl-handbook-reference**, professional edition, **tonnesoftware.com/elsie.html**.

[2]LTspice, Linear Technology Corp., **www.linear.com/designtools/software/#LTspice**.

[3]See the Digital Modulation section, Fig. 8.11 and associated text; *The ARRL Handbook Book,* 2017 Edition. ARRL item no. 0628, available from your ARRL dealer, or from the ARRL Store, Telephone toll-free in the US 888-277-5289, or 860-594-0355, fax 860-594-0303; **www.arrl.org/shop/**; **pubsales@arrl.org**.

[4]**www.eham.net/reviews/detail/58**.

[5]Ed Wetherhold, **w3nqn@comcast.net**.

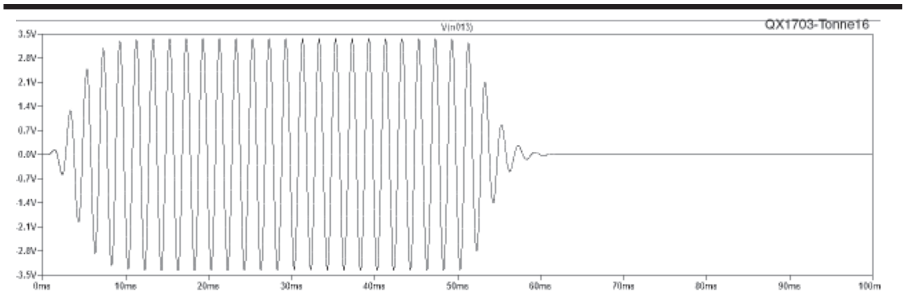

Figure 16 — Output of the active filter with the applied burst.

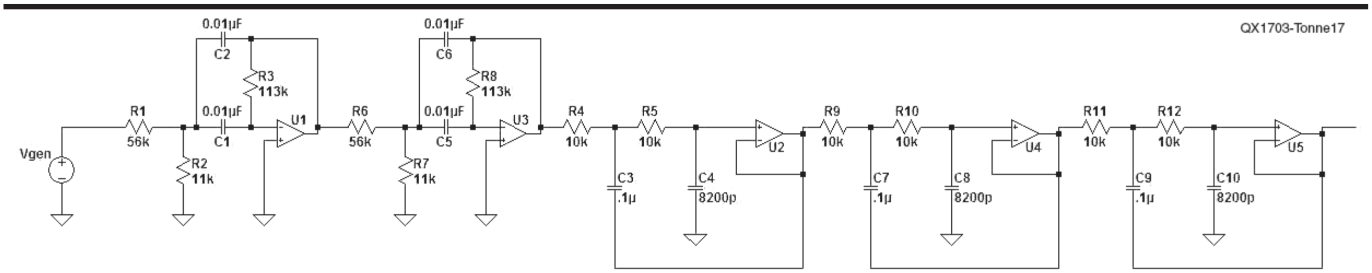

Figure 17 — Schematic of an equivalent active filter.

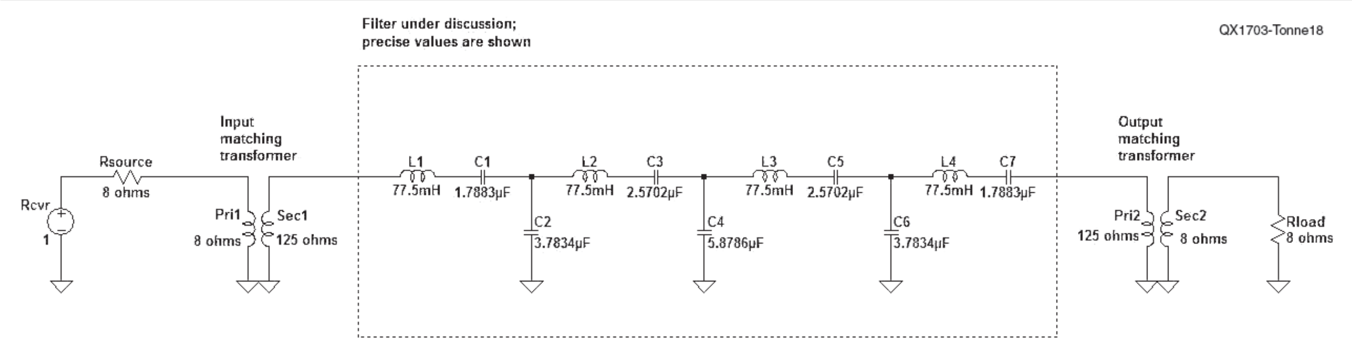

Figure 18 — Schematic of the passive add-on band-pass filter.