# A 500-Hz Bandpass Filter for Wobbulated-Tone TEMPEST Testing

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**An inexpensive and practical inductor-capacitor bandpass filter can be designed and assembled to make a five-resonator bandpass filter.**

## INTRODUCTION

One of the TEMPEST tests performed on secure speech communications systems involves using a wobbulated tone to simulate a speech input signal. While the equipment under test (EUT) is activated with the simulated speech signal, the non-speech lines are tested by connecting a high-gain audio amplifier and headset to each line while listening for the presence of the wobbulated tone. If the wobbulated tone is detected, it indicates that the security of the speech communications system may be compromised.

In spite of the distinctive sound of the wobbulated tone, the tone may be difficult to hear if the audio detection system has an unrestricted audio bandwidth so that all audio signals from 60 Hz to 20 kHz are passed to the ears of the tester. Using such a wideband detection system can eventually cause listening fatigue because the ear is continually subjected to hum, broadband noise, clock harmonics, heterodynes and hiss over the entire audio range.

To lessen listening fatigue and to make it easier to detect the wobbulated tone, a passive inductor-capacitor (LC) bandpass filter (BPF) should be placed either in front of the audio detection system or between the detection system audio output and the headset. This form of preselection will limit the audio spectrum to a passband just wide enough to pass only the wobbulated tone and thereby eliminate most of the undesired noise. This article explains how an inexpensive and practical LC BPF can be designed and assembled to make a 5-resonator BPF using surplus 88-mH inductors, seven capacitors and two transformers.

## BACKGROUND

A former TEMPEST test specification, NACSIM 5100A, specified the wobbulated tone to have a center frequency of 1000 Hz with a deviation limit of about 150 Hz above and below the center frequency. An LC BPF suitable for a 1000-Hz wobbulated tone was described in *ITEM* 1989[1] using surplus inductors, and this design would normally take care of the audio preselection requirement. However, a new TEMPEST test specification was recently released in which many of the previous test requirements of NACSIM 5100A were revised. For example, one of the new requirements now states that the speech-simulated test signal shall be a wobbulated test tone of 500 Hz. Because this is a substantial change from the previous frequency of 1000 Hz, a new LC BPF design is required as the old design is no longer usable.

Figure 1 shows a graphical representation of the wobbulated tone acceptable for use as the new simulated speech signal. Using this figure as a guide, an LC BPF will be designed that has a 3-dB bandwidth less than the maximum frequency deviation and greater than the minimum frequency deviation. Thus the BPF will be suitable for receiving a wobbulated tone which complies with the requirements of Figure 1.

The minimum and maximum acceptable frequency deviations of the 500-Hz tone are ±50 Hz and ±250 Hz, or bandwidths of 100 Hz and 500 Hz. As long as the wobbulated tone variations fall within these limitations it is acceptable for use. These tone deviations can be more generally specified in terms of relative bandwidth. This is done by specifying the bandwidth (BW) of the deviations as a percentage of the center frequency (Fc), i.e., BW% = 100*BW/Fc. For example, the minimum percentage BW = 100*100/500 or 20%, and the maximum percentage BW = 100*500/500 or 100%. The percentage 3-dB bandwidth of the BPF will be the same as the percentage BW deviation of the wobbulated tone.

To optimize the signal-to-noise ratio, the bandwidth of the BPF should be as narrow as possible. Consequently, an optimum bandpass response would be equal to the minimum permissible relative bandwidth of 20%; however, it will later be shown that in order to simplify the realization of the BPF it is necessary that a relative bandwidth of about 50% be used.

The corresponding bandwidth of the BPF will be about 250 Hz, or about half of the maximum per-

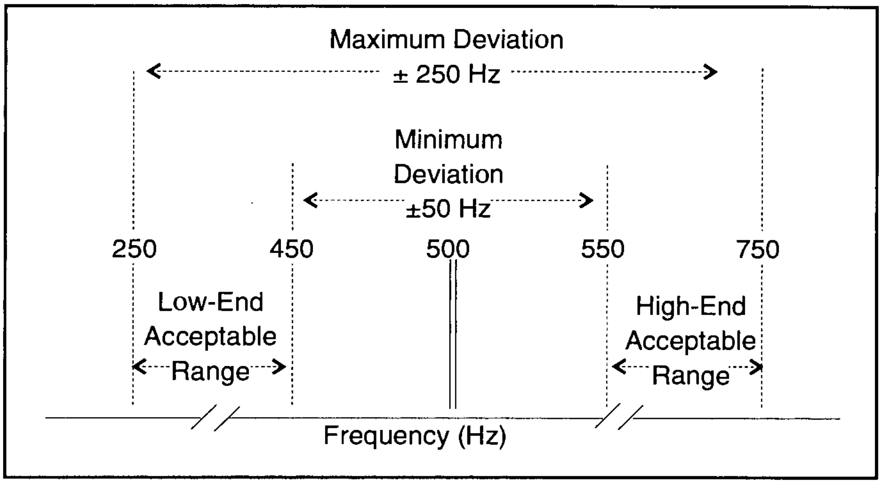


***Figure 1**. The Permissible Maximum and Minimum Deviations of a Wobbulated 500-Hz Test Signal. The corresponding maximum and minimum relative percentage bandwidths of a bandpass filter, optimized to receive this signal, are 20% and 100%.*

missible deviation. The corresponding lower and upper 3-dB cutoff frequencies will be about 390 and 640 Hz. These frequency extremes fall comfortably within the acceptable ranges specified in Figure 1. Even though the filter bandwidth is not as narrow as it could be, it is narrow enough so that most of the undesired audio noise is rejected.

## DESIGN OF AN OPTIMUM BPF

The design of a BPF is relatively simple and straightforward, and there are many sources available to explain the procedure.[2,3,4] However, the procedure becomes much more complicated when it is necessary to find an optimum design that not only has acceptable performance parameters such as center frequency, bandwidth, selectivity and impedance level, but is also easy to assemble with inexpensive components.

Because the deviation requirements for the wobbulated tone are relatively lenient, it is possible to select a suitable filter bandwidth that allows all the desired filter performance requirements to be conveniently realized.

## BPF DESIGN PARAMETERS

The following parameters of center frequency, bandwidth, selectivity and impedance level will be individually considered.

**Center Frequency**. Because the TEMPEST test requirement is very specific concerning the frequency of the wobbulated tone, this parameter will not be compromised to simplify the design; consequently, the BPF center frequency will be exactly 500 Hz.

**Bandwidth.** The permissible 3-dB bandwidth of the filter can be between 100 and 500 Hz. A bandwidth of about 250 Hz will be used because a design having this bandwidth can be easily achieved with surplus 88-mH inductors and inexpensive transformers.

**Selectivity**. No requirement regarding the BPF selectivity is mentioned in the test specification; consequently, this parameter is left up to the judgment of the filter designer. A 5-resonator bandpass filter configuration was selected for this application because it is a reasonable compromise between selectivity, cost and ease of construction. The filter skirt selectivity is about 55 dB per octave, and the attenuation below 250 Hz and above 1 kHz is 45 dB or more. The reflection coefficient of the chosen design is 0.044% which means the filter performance will be unaffected by minor variations in the termination impedance.

**Impedance Level**. Because 50 ohms is a standard impedance specified in many of the TEMPEST test requirements, the completed BPF should be able to be terminated with this impedance. Since the filter may be inserted between the 8-ohm output of a receiver and a headset for aural detection and evaluation, the filter should also be able to be terminated with an 8-ohm impedance, which is a common headset impedance. Consequently, an optimum BPF design should have the capability of being easily switched between impedance levels of either 50 ohms or 8 ohms. The BPF design to be discussed has this capability. The following discussion explains how the selected filter design achieves this impedance level change using two standard commercial transformers.

## MATCHING THE BPF TO 50- OR 8-OHM TERMINATIONS

Many small audio transformers are available from Mouser Electronics[5] which will match an 8-ohm source or load to a filter having an impedance level of 120, 200, 500, 1000 or 1200 ohms. Both the low and high impedance windings of these transformers are center-tapped. Of these five types, only the 8-to-200-ohm transformer has the desired capability of matching a 200-ohm filter to either an 8- or 50-ohm source and load. This can be accomplished by connecting an 8-ohm source or load to the 8-ohm winding or by connecting a 50-ohm source or load to the center tap of the 200-ohm winding. The impedance to ground at the center tap of the 200-ohm winding is one quarter of the 200-ohm impedance, or 50 ohms. Consequently, in order to satisfy the requirement of matching the filter to either 8- or 50-ohm terminations, it is necessary that the BPF have a nominal design impedance level of 200 ohms so an 8/200-ohm center-tapped transformer can be installed on each end of the filter.

In the calculations to follow, the desired termination impedance of 200 ohms is increased by about 18 ohms to anticipate the additional resistances associated with the primary and secondary windings of the transformer and also the resistances associated with the inductors, L1 and L5.

## BPF REALIZATION USING 88-mH INDUCTORS

The low cost of realizing the BPF design is due to using 88-mH telephone-line loading coils that were discarded as non-salvageable scrap by the telephone company. The inductors used in this filter consist of one 5-inductor stack contained in a cardboard wrapper plus two separate bifilar-wound 88-mH inductors stuck on each end of the stack. Figure 2 shows a typical inductor stack with two separate bifilar-wound 88-mH inductors.

Each of the five inductors in the stack and both of the external inductors have two 22-mH windings on a molybdenum permalloy powder (MPP) core. The two windings are connected in series to make a nominal inductance value of 88 mH. Due to variations in the core permeability, the actual series inductance will vary between 85 and 89 mH. The nominal value of 88 mH is used in the following discussion and calculations.

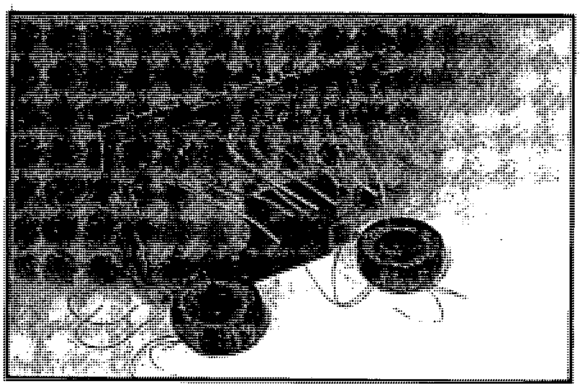

***Figure 2.*** *A Typical 88-mH Inductor Stack With Two Bifilar-wound 88-mH Inductors Which are Used in the 500-Hz Bandpass Filter Construction. A plastic component mounting clip provides a convenient means of mounting the stack.*

## DESIGN PROCEDURE

Although the design procedure for the 500-Hz BPF is relatively lengthy, the complete procedure is explained in detail in Appendix A so those wishing to confirm the 500-Hz design or wishing to calculate a design having a different center frequency may do so. Figure 3 shows the schematic diagram resulting from the calculations given in Appendix A, except that the values of capacitors C6 and C7 were determined experimentally by observing the effect of capacitance changes on the passband return loss response of the filter. The listed values of C6 and C7 produced the optimum passband return loss response.

## BPF ASSEMBLY

Figure 4 shows the wiring of the 500-Hz BPF using one 5-inductor stack and two separate 88-mH inductors. Use the following step-by-step procedure to obtain an error-free filter assembly:

1. Connect the leads of L2 and L4 in series by soldering the red start lead to the green finish lead as shown in Figure 4(A). The polyurethane film insulation does not need to be scraped off because the insulation will vaporize if the leads are soldered with a 750°F solder-iron tip.
2. Trim all the leads soldered to the stack terminals to a suitable length and wire the stack terminals as shown in Figure 4(B). About half of the leads are not needed and are removed from the stack.
3. Secure all five capacitors to the surface of the inductor stack with silicone sealer and connect their leads to the stack terminals as shown in Figure 4(B).
4. Secure L2 and L4 to the ends of the inductor stack with sil-

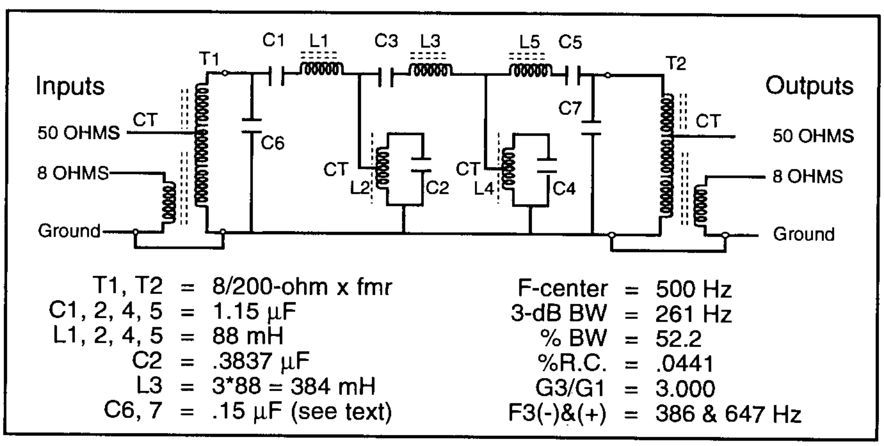


***Figure 3.*** *The Schematic Diagram and Design Parameters of a 500-Hz Bandpass Filter That is Optimized for Receiving the 500-Hz Wobbulated Test Signal.*

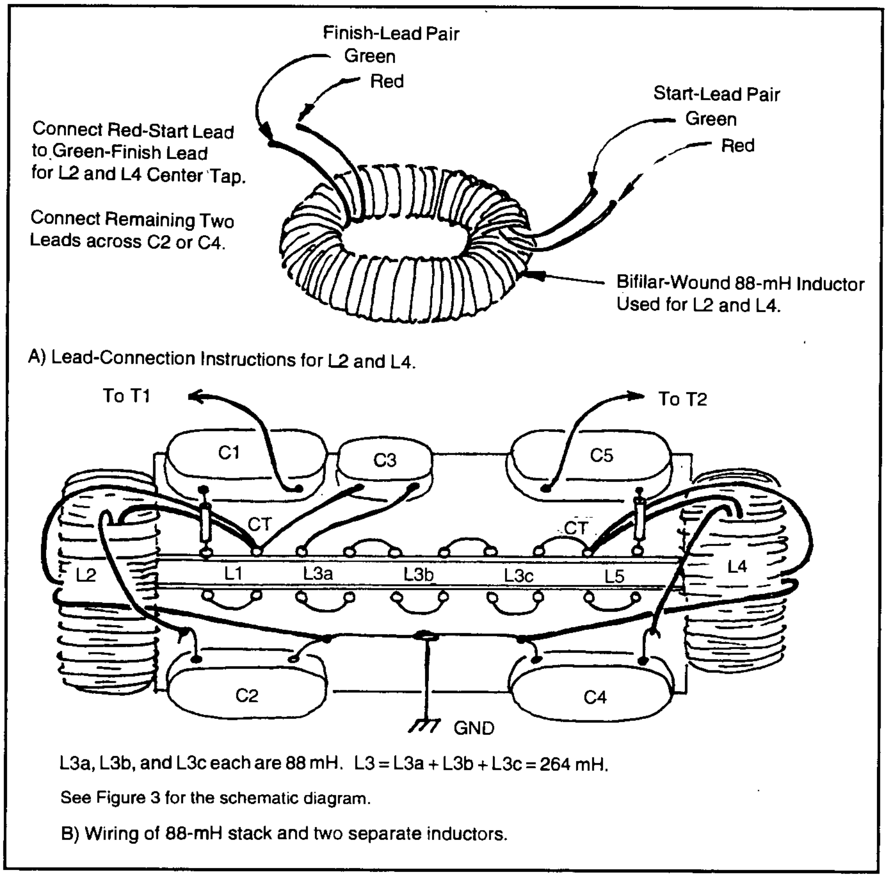


***Figure 4**. Wiring of the 500-Hz Bandpass Filter Using One Inductor Stack, Two 88-mH Inductors and Five Capacitors.*

*(A) Lead-connection instructions for L2 and L4: connect red-start lead to green-finish lead for L2 and L4 center tap; connect remaining two leads across C2 or C4.*

*(B) Wiring of 88-mH stack and two separate inductors. L3a, L3b and L3c each are 88 mH. L3 = L3a + L3b + L3c = 264 mH.*

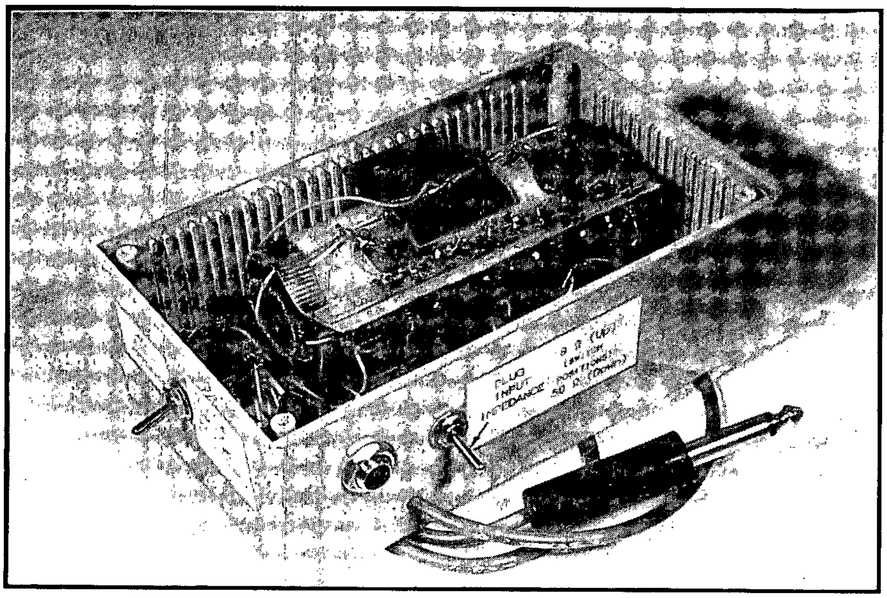

***Figure 5.** The Installation of the Bandpass Filter in a Mouser Plastic Box. The input and output connections are made with a standard 1/4-inch phone plug and jack, respectively.*

icone sealer and solder their leads to the stack terminals and to the leads of capacitors C2 and C4 as shown in Figure 4(B).

5. While the silicone sealer is hardening, obtain a plastic box large enough to hold all the components. The Mouser plastic box, Stock No. 400-1562 (5.9 x 3.5 x 2.2 inches), is recommended. Punch or drill holes for the stack mounting clip, two miniature single-pole double-throw (SPDT) switches and the phone jack and plug cable. Secure the two transformers with silicone sealer in the corners of the box and complete the wiring of the two switches, phone jack, plug and transformers. One of the switches is wired to connect the phone plug (signal input) to either the 8-ohm or 50-ohm (center tap) terminal of T1. The other switch is wired to connect the phone jack (signal output) to either the 8-ohm or 50-ohm (center tap) terminal of T2. Figure 5 shows the filter assembled in the recommended Mouser plastic box.

*Note: If you wish to assemble this filter, send a self-addressed stamped business-sized envelope to the author for details on how to obtain all the parts.*

## BPF RESPONSE TEST RESULTS

After the BPF was assembled, it was tested for both relative attenuation and return loss. Both tests were made at impedance levels of 50 and 218 ohms. The 50-ohm test was made to demonstrate that the filter and transformers will satisfactorily perform at a 50-ohm impedance level. The 218-ohm test was made (with the transformers omitted) because this is the design impedance level of the filter, and to obtain a true indication of the filter performance

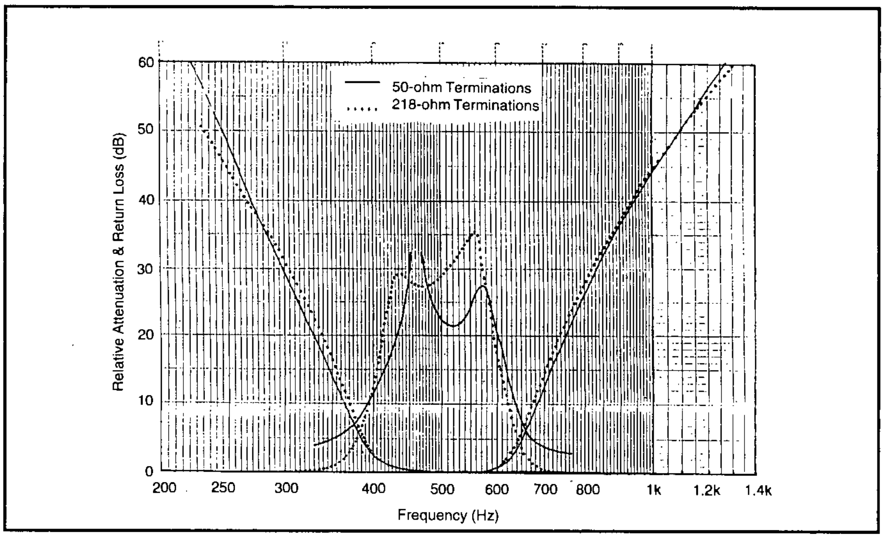


***Figure 6.*** *The Measured Relative Attenuation and Return Loss Responses of the 500-Hz Bandpass Filter. For the 50-ohm terminations (solid lines), the attenuation and return loss responses were measured between the center taps of transformers T1 and T2. For the 218-ohm terminations (dotted lines), transformers T1 and T2 and capacitors C6 and C7 were removed and the response measurements were made at the ends of C1 and C5 as shown in Figure 3.*

it is necessary that it be tested with its design impedance terminations. Figure 6 shows the curves of measured relative attenuation and return loss.

## INSERTION LOSS AND RELATIVE ATTENUATION

The insertion loss of the BPF (less the transformers) was 2.0 dB at 500 Hz. With the transformers included, the loss was about 3.6 dB when measured between the transformer center taps of the 200-ohm windings.

The BPF attenuation levels were measured relative to zero dB at 500 Hz. For the 218-ohm termination test, the impedance of a 600-ohm audio signal generator was modified to provide a 218-ohm signal source for the filter, and the filter output was terminated in a 218-ohm resistive load. The measured 3-dB bandwidth of 230 Hz (627 - 397) is about 12% narrower than the calculated bandwidth of 261 Hz. The narrowed bandwidth is attributed to a lower than optimum inductor Q at the 500-Hz center frequency. The measured Q of the 88-mH inductors at 500 Hz is 28, and a Q of 38 is required if the measured bandwidth is to be very close to the calculated bandwidth. A good match between the calculated and measured bandwidths will occur when the inductor Q is greater than 20*Fc/B3. In this case, a satisfactory inductor Q should be greater than 20*500/261 = 38 at 500 Hz. Nevertheless, the inductor Q of 28 is adequate for this particular application, and the measured percentage bandwidth, 100*230/500 = 46%, is still well within the permissible 20% to 100% bandwidth specified in Figure 1.

With transformers T1 and T2 installed, the relative attenuation was measured in a 50-ohm system by using the center taps of the 200-ohm windings as the input and output connections. The response was very similar to that without the transformers. In either case, the relative attenuation responses were satisfactory.

## RETURN LOSS

The return loss responses of the terminated filter were measured using the return loss bridge (RLB) described in the 1993 *ITEM Update* article.[6] The filter return loss at both the 218- and 50-ohm levels was measured with the appropriate signal source impedance, with the proper resistors installed in the RLB and with the BPF output properly terminated. The return loss responses for the 218- and 50-ohm tests are shown by the dotted and solid lines in Figure 6.

The minimum return loss of the filter itself in a 218-ohm test system (dotted line) was 27 dB at about 475 Hz with a peak on either side of 475 Hz. Although the return loss peaks were unequal, the difference was of no consequence because the 27-dB minimum return loss was quite adequate.

With transformers T1 and T2 in place and before capacitors C6 and C7 were installed, the 50-ohm minimum return loss was an unsatisfactory 17 dB at 515 Hz with two pronounced peaks (>35 dB) at 457 and 585 Hz. After tuning out the undesired reactances associated with the transformers (by installing a 0.15-µF capacitor across each of the 200-ohm windings), the 50-ohm minimum return loss was raised to an acceptable level of about 21 dB. Any further tuning was considered unnecessary and unlikely to produce additional improvements.

As the results of the relative attenuation and return loss tests were satisfactory, all testing was concluded. The labeling of the filter box was then completed and the box cover installed.

## SUMMARY

A bandpass filter centered on 500 Hz was found to be necessary because of a new TEMPEST test specification requiring the use of a 500-Hz wobbulated tone as a simulated speech signal. The reception of the wobbulated tone is significantly enhanced if the signal detected on the line being tested is restricted to only that limited portion of the audio spec-

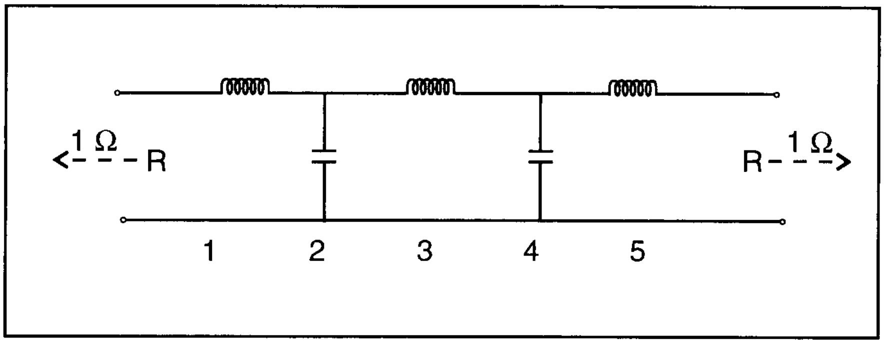


***Figure A1****. The Chebyshev Low-pass Prototype Used in the Derivation of 500-Hz 5-resonator BPF. The branches are numbered 1 to 5 from left to right and the corresponding normalized component values are listed in Table A1.*

| Reflection Coefficient(%) | G1,G5 (H) | G2,G4 (F) | G 3 (H) | G2/G1 Ratio | G3/G1 Ratio | Return Loss (dB) |
|---|---|---|---|---|---|---|
| 0.044 | .1054 | .2625 | .3162 | 2.4905 | 3.000 | 67.1 |
| 2.768 | .1417 | .2704 | .3188 | 1.9083 | 2.250 | 31.2 |
| 6.302 | .1642 | .2657 | .3284 | 1.6181 | 2.000 | 24.0 |

***Table A1****. The Chebyshev low-pass prototype values are normalized for 1-ohm terminations and for a 3-dB cutoff frequency of 1 Hz. The letter "G" is used to signify a normalized value. Columns (H) and (F) list inductances in henries and capacitances in farads.*

trum containing the wobbulated tone. The design of an optimized 500-Hz bandpass filter was explained and the inexpensive assembly of the filter was demonstrated using seven 88-mH inductors, two transformers and seven capacitors. By using two 8/200-ohm transformers, the completed filter was capable of being used either at an 8-ohm or 50-ohm impedance level. The performance of the BPF was confirmed by plotting the relative attenuation and return loss responses for both the 50-ohm and 218-ohm terminations.

Because of the satisfactory performance, easy assembly and low cost of this filter, the TEMPEST test engineer has a viable alternative to purchasing a similar filter from commercial sources.

## ACKNOWLEDGEMENTS

The author gratefully acknowledges the assistance of Rex Cox, Heyward Preacher and St. John Martin in reviewing this article.

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5. Mouser Electronics, Central Distribution Center, 2401 Highway 287 North, Mansfield, TX 76063-4827. 1-800-346-6873. Telephone to request a free catalog.
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## APPENDIX A: DERIVATION OF CALCULATIONS FOR THE 500-HZ BANDPASS FILTER

This bandpass filter (BPF) is based on a 5-element Chebyshev low-pass design having an inductor input/output configuration as shown in Figure A1.

Because of the equal terminations specified in Figure A1, G1 = G5 and G2 = G4. The three designs listed in Table A1 were selected for tabulation because their G3/G1 ratios match similar L3/L1 inductor ratios available in a standard 88-mH 5-inductor stack.

The low-pass design for a G3/G1 ratio of 3.000 is selected to be the low-pass prototype because it produces an optimum design for this particular application. The normalized component values of this filter, as listed in Table A1, are scaled to a 3-dB cutoff frequency (F3) somewhere between 100 and 500 Hz and at an impedance level (R) that produces an optimum design that can be realized with only 88-mH inductors. The scaled low-pass filter is transformed into a bandpass design having a 3-dB bandwidth (B3) equal to the F3 frequency of the prototype low-pass filter and having a center frequency (Fc) of 500 Hz as specified in Figure 1.

The input and output transformers used to couple the BPF to its source and load also match the filter to either 50 or 8 ohms. These two impedances are common values for a typical detection system and headset, respectively.

The steps of the derivation procedure follow:

1. To use the 88-mH inductor stack in an optimum configuration, it is necessary to assume that the design termination resistance (R) is initially four times greater than the final value, and inductors L1 and L5 are 4 times 88 = 352 mH (Figure A1). The reason for

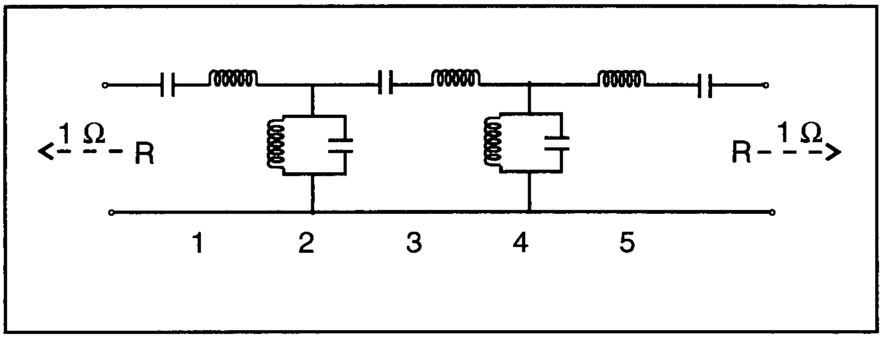



***Figure A2.*** *The Schematic Diagram of the BPF After Completion of the Low-pass-to-Bandpass Transformation. The components assume the number designation of the branch in which they appear. All branches are resonated at the BPF center frequency.*

this will become obvious at the end of the derivation explanation.

2. The low-pass (LP) prototype design is transformed into a bandpass (BP) filter having a center frequency of 500 Hz and a 3-dB bandwidth (B3) between 100 and 500 Hz. The LP-to-BP transformation is accomplished by resonating the capacitors and inductors in Figure A1 to 500 Hz. Figure A2 shows the resulting BPF configuration after the transformation. The value of R corresponding to Fc = 500 Hz is the first design parameter to be calculated.

3. The different component values and frequency parameters of the low-pass and bandpass filters are related by the following equations which determine the value of R:
   a. F3 = G1*R/L1, where F3 is the 3-dB cutoff frequency in hertz of the low-pass prototype filter in Figure A1; G1 is the normalized component value given in Table A1; R is the termination resistance in ohms and L1 is the scaled inductance (.352) in henries, as was specified in paragraph (1) above.
   b. F3 = G2/(R*C2), where C2 is the scaled value of G2 in farads and G2 is the normalized value of C2. F3 was defined in step 3a.
   c. C2 = .0253303/(L2*Fc$^2$), where Fc is the center frequency in hertz of the BPF and L2 is the inductance in henries that resonates C2 to Fc.

4. In equation 3b, replace C2 with 0.0253303/(L2*Fc$^2$) from equation 3c. Then set F3 in 3a equal to F3 in 3b and solve for R in terms of G1, G2, L1, L2 and Fc:

   G1*R/L1 = G2/[R*(.0253303/L2*Fc$^2$)]=
   39.4784*G2*L2*Fc$^2$/R

   The equation is arranged to give R$^2$ in terms of G1, G2, L1, L2 and Fc as follows: R$^2$ = 39.4784*L1*L2*G2*Fc$^2$/G1, where L1 and L2 are in henries and Fc is in hertz. L1 is 0.352 H as specified in step 1.

5. The value of L2 can be selected to produce an acceptable value of R. A value of L2 = 0.088H will be selected, and this value will be substituted in the equation along with the other parameters to find the corresponding value of R. As previously mentioned, the low-pass normalized values for a G3/G1 ratio of 3 will be used. For this design, L3 is three times the value of L1.

R$^2$ = 39.4784*0.352*.088*.2625*500$^2$/.1054 =
80251.7/.1054 = 761401.33
R = 872.6 ohms

The corresponding value of F3 and the BPF bandwidth (B3) can be calculated from Equation 3a:

F3 = B3 = .1054*872.6/.352 = 261.3 Hz

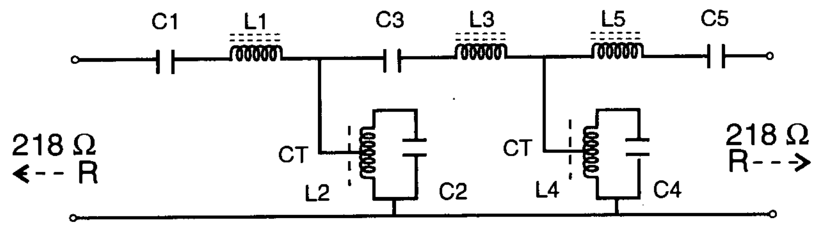
The 3-dB bandwidth (B3) of the BPF is equal to the 3-dB cutoff frequency (F3) of the low-pass prototype as a consequence of the LP-to-BP transformation procedure. The 3-dB lower and upper frequencies of the bandpass response are calculated using the equations:

F3(-) = SQR(Fc$^2$ + X$^2$) - X, where X = B3/2, and
F3(+) = F3(-) + B3

From these equations, F3(-) = 386 Hz and F3(+) = 647 Hz. Because the 3-dB frequencies are within the low and high-end acceptable ranges specified in Figure 1, the derived BPF design is acceptable.

6. Using the previously given equations, all component values of the BPF shown in Figure A2 are calculated as follows:

L1 = .352H, as specified in paragraph (1)
C1, C5 = .02533/(L1*Fc$^2$) = .02533/(.352*500$^2$)
= .2878 μF
L2, L4 = .088H, as specified in paragraph (5)
C2, C4 = .02533/(L2*Fc$^2$) = .02533/(.088*500$^2$)
= 1.151 μF
C3 = C1/3 = .2878/3 = .095933 μF
L3 = L1*3 = .352*3 = 1.056 H
All LC products = 101.3 mHμF




C1, 2, 4 and 5 = 1.151 µF
C3 = 0.384 µF
L1, 2, 4, 5 = 88 mH
L3 = 264 mH
R = 218 ohms

Fc = 500 Hz
BW3 = 261 Hz
% BW = 100*B3/Fc = 52.2%
F3(-) = 386 Hz
F3(+) = 647 Hz

***Figure A3**. The schematic diagram shows all component values and calculated parameters of the 500-Hz bandpass filter which was optimized for assembly with seven standard 88-mH inductors.*

The only thing left to demonstrate is how the calculated termination impedance (R) of 872.6 ohms can be conveniently accommodated using commercially available transformers.

7. To obtain an impedance level one quarter of R, or 872.6/4 = 218 ohms, that can be matched by a standard 8/200-ohm transformer (Mouser Part No. 42TU200, 0.4-watt, 8/200-ohm), a simple modification will be made to the BPF diagram of Figure A2. The two nodes Ll-C3 and L3-L5 of the series branches LC1, LC3 and LC5, will be connected to the center taps of L2 and L4. With this modification, the series branch reactances all become one quarter of their former values. The R, L1, L3 and L5 resistance and inductance values are quartered and the C1, C3 and C5 capacitance values are quadrupled. C2, C4, L2 and L4 remain unchanged. Except for C3 and L3, all capacitor and inductor values now become identical.

L1, L2, L4 and L5 can each be realized with one 88-mH inductor, while L3 can be realized with three series-connected 88-mH inductors. Figure A3 shows the final diagram of the 500-Hz BPF and all related parameters. The reason for beginning the design procedure with R = 872.6 ohms and L1 and L5 = .352 H now becomes obvious.

Although the filter design termination impedance is 218 ohms, the actual termination impedance seen by the BPF will be 232 ohms. The 232-ohm value results from summing the 200-ohm secondary impedance, the transformer primary winding resistance (as referred to the secondary winding), the secondary winding resistance and the resistance of the input (or output) inductor. Because the actual termination impedance is within 7% of the design value, there will be no adverse effects on the BPF performance because the very low reflection coefficient makes the BPF relatively insensitive to variations in its termination impedance. The measured 3-dB bandwidth will be about 12% narrower than the calculated bandwidth because of the low inductor Q around 500 Hz. Nevertheless, the measured bandwidth is still acceptable as it is well within the permissible range of the deviation specification given in Figure 1. This concludes the explanation of the 500-Hz BPF design procedure.

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