SIMPLIFIED DESIGN AND CONSTRUCTION OF AUDIO-FREQUENCY 50-OHM BANDPASS FILTERS

Test technicians and engineers can now design and construct 50-ohm bandpass filters useful in limiting the bandwidths of non-tunable detection systems.

Edward E. Wetherhold, Signal Analysis Center, Honeywell Inc., Annapolis, MD

INTRODUCTION

The increased emphasis on testing personal computers (PCs) for compliance with the radiation and conduction requirements of certain test specifications necessitates the use of low-frequency audio bandpass filters for defining the bandwidths of non-tunable detection systems. These filters are needed because the commonly used PC serial input/output data rates of 300 and 600 bits/second (b/s) require cutoff frequencies as low as 150 Hz. Bandpass filters (BPFs) are also useful for limiting the audio bandwidth of detection systems used when testing analog speech communication systems.

Constructing BPFs for use in the high audio frequency range (above 5 kHz) presents no problem because the inductors usually require less than 100 turns and are easily hand-wound on toroidal moly-perm cores. However, for cutoff frequencies as low as 150 Hz, hand winding inductors becomes impractical because several hundred turns are needed. The purchase of inductors from an inductor manufacturer or the purchase of a BPF from a filter manufacturer has the disadvantages of high cost and delivery delay. A more satisfactory alternative is for an electronics technican to assemble a suitable BPF in the test laboratory using conveniently available standard parts.

Previously, the lab construction of low-frequency audio BPFs was impractical because of the large number of turns required to wind the inductors. However, a new design and construction technique using surplus load coil stacks to satisfy the inductor requirements now makes it feasible to construct this filter type easily and inexpensively. This article provides all the information necessary to design and to construct audio-frequency 50-ohm BPFs, and several examples demonstrate the simplicity and versatility of this new design procedure. These examples are directly applicable for use in accordance with a commonly used test specification familiar to many ITEM readers.

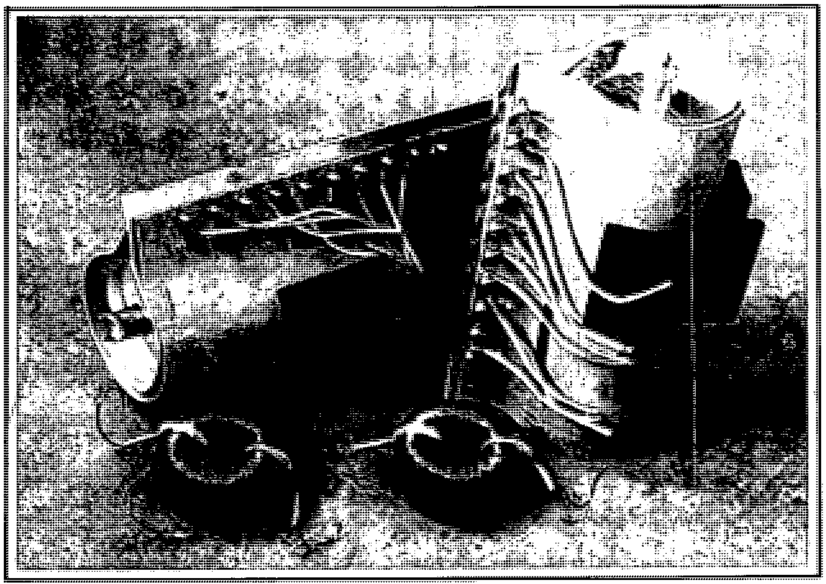


Figure 1. Two Typical 88-mH Inductor Stacks and Two 44-mH Inductors Used in the Bandpass Filter Construction. Plastic component mounting clips securely grasp the stacks for convenient mounting on a base.

SURPLUS LOAD COIL STACKS

Millions of load coils are used on telephone lines throughout the U.S. to optimize the transmission of audio signals. The coils are assembled in a 5-coil stack with a cylindrical cardboard wrap, and the coil leads are terminated in two rows of ten terminals per row. Figure 1 shows two typical 88-mH inductor stacks and two separate 44-mH inductors used in the BPF construction to be discussed. The load coil stacks become available as nonsalvagable scrap when the telephone company dismantles a telephone line. Although these inductors are not reuseable by the telephone company, they are highly valued by radio amateurs for audio filter construction; and many articles have been published on this subject.[1-4] Enterprising electronics technicians and engineers can also make good use of these inductors, which are available from several sources*, including junkyards specializing in electronics scrap.

The two frequently encountered toroidal load coils available have values of 88 mH (most common) and 44 mH (less common), and each coil has two toroidal windings, nominally 22 or 11 mH. When the windings are connected in series aiding, the total nominal inductance is 88 or 44 mH, respectively; and the inductor is specified by its series inductance. When increased accuracy is required, the leakage inductance of the windings must be considered; and the nominal values of 11 and 22 mH are more accurately given as 10.9 and 21.8 mH, respectively. Inductor Q is about 50 at 1000 Hz and increases to a maximum of about 160 to 7 kHz; whereafter, the Q declines to about 50 at 40 kHz. It will be demonstrated that the inductor Q for bandpass filter applications is adequate even for cutoff frequencies as low as 150 Hz.

One of the advantages of these surplus inductor stacks is that they are already in a convenient-to-use assembly with terminals that allow the inductors to be wired, in different combinations, to achieve the required values. Also, two separate inductors may be glued to the ends of the stack when additional inductors are needed. If necessary these end inductors are modified easily by removing turns to achieve smaller values. The presence of a center tap (when the windings are connected in series) is an important and necessary feature in some of the bandpass filters to be discussed. The disadvantage of bulk and weight, as compared to the smaller and lighter active filter, is acceptable in exchange

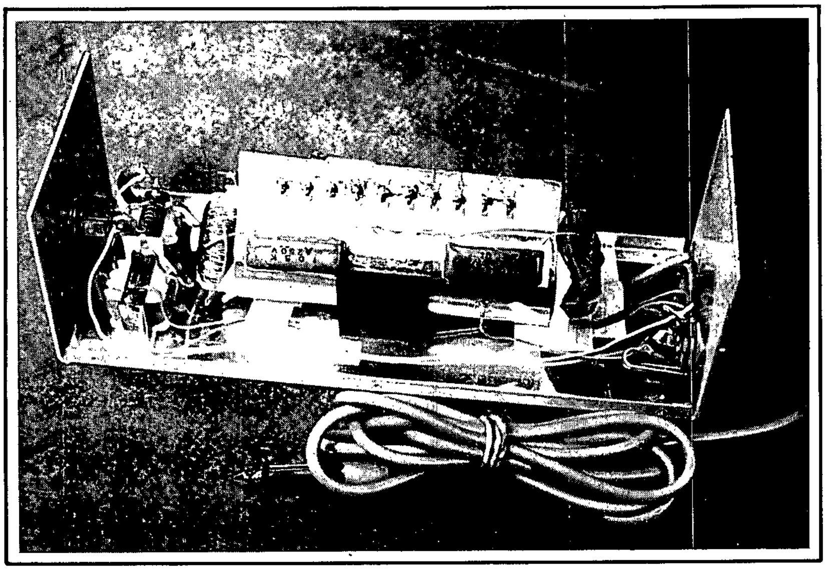
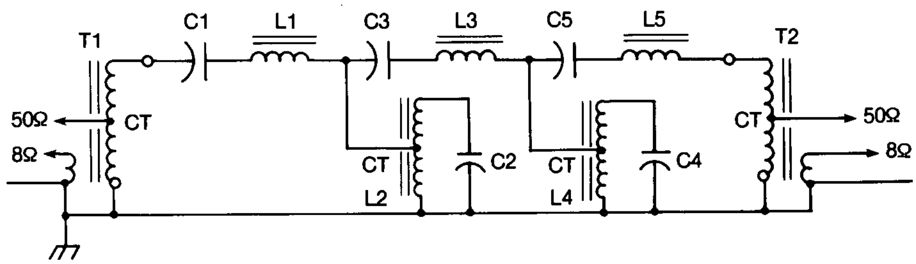


Figure 2. The Narrowband Bandpass Filter Assembled in a Crown CR-800 Aluminum Box. The two 8/200-ohm center-tapped transformers are glued to the bottom left side of the box; the phone jack is mounted on the opposite end. The two 44-mH inductors and five capacitors are secured to the ends and sides of the stack with silicone sealer.



C1, C5—0.292 μF
C2, C4—1.036 μF
C3—0.0973 μF

L1, L5—88.0 mH
L2, L4—24.8 mH ct (modified 44-mH inductor. See text for details.)
L3—264 mH (three 88-mH inductors connected in series)

T1, T2—transformer, 8/200-ohm, ct, 0.4-watt (Mouser 42TU200)

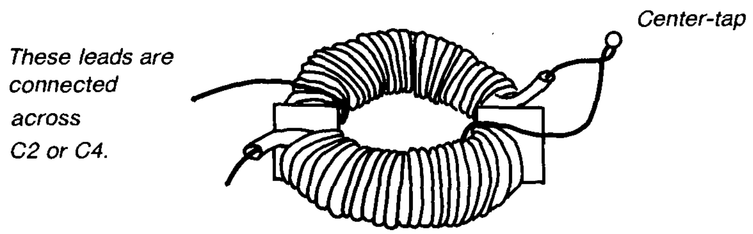
All capacitors are 100-V metallized Mylar. If necessary, two capacitors may be paralleled to obtain the design values within one percent.

Figure 3. Schematic Diagram of the Narrowband 993-Hz Bandpass Filter. All L-C circuits are resonated at 993 Hz. A geometric center frequency of 993 Hz is used so that the 6-dB frequencies on the filter response plot are about 150 Hz above and below 1 KHz. C1 and C5 can be obtained with paralleled .27-μf and .022-μf capacitors. Figure 4 shows the wiring diagram of the filter.

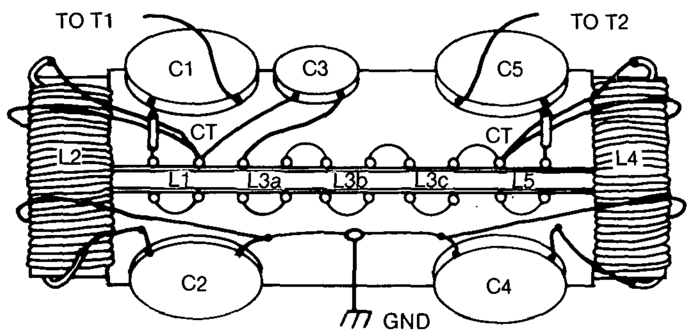
for the ease of design and assembly. Also, the noise-free character of the passive filter makes it especially appropriate for use in front of low-noise amplifiers.

BANDPASS FILTERS FOR TESTING ANALOG SPEECH COMMUNICATION SYSTEMS

When testing analog speech communication systems for spurious speech correlated emanations, the customary practice is to use a wobbulated 1000-Hz input test signal as a simulated speech signal. Then the non-speech lines to be tested are searched aurally for the presence of the 1000-Hz wobbulated tone. Usually, the audio detection system has an unnecessarily unrestricted audio bandpass so that any signal from 60 Hz to 20 kHz is passed to the ears of the tester. Such a wideband detection system eventually causes listening fatigue because the ear is subjected to continuous hum, noise, clock harmonics, hetrodynes and hiss over the entire audio range. To lessen listening fatigue, a passive inductor-capacitor (LC) BPF is recommended. This will limit the audio spectrum to a passband just wide enough to pass only the wobbulated 1000-Hz test signal. Also useful is a wideband BPF for passing only to the speech range between 300 and 3000 Hz. The following discussion explains how load coils can be used to design and to construct narrowband and wideband BPFs for use in audio detection systems.



(A) Lead connection details for L2 and L4.



(B) Narrowband bandpass filter assembly showing the wiring details of the 88-mH stack and two modified 44-mH inductors. L3a, L3b and L3c are each 88 mH, and when connected in series they equal 264 mH. See Figure 3 for the filter schematic diagram.

Figure 4. The pictorial diagrams show how to connect the leads of the modified 44-mH inductors and how to wire the 88-mH stack for the narrowband bandpass filter. The modified 44-mH inductors (L2 and L4) are fastened to each end of the inductor stack with silicone sealer.

General Bandpass Filter Requirements

A five-resonator BPF will be used because the skirt selectivity is quite adequate and because the filter can be inexpensively and easily assembled using an inductor stack and two separate inductors. To comply with the impedance requirements of the test specification, the filter is designed for 50-ohm terminations and a maximum VSWR of less than 1.20. A Chebyshev design with a maximum reflection coefficient of nine percent and a maximum VSWR of 1.198 is selected to comply with the 10-ohm maximum impedance variation permitted by the test specification. Figure 2 shows how the narrowband BPF looks when assembled in a standard commercial aluminum box.

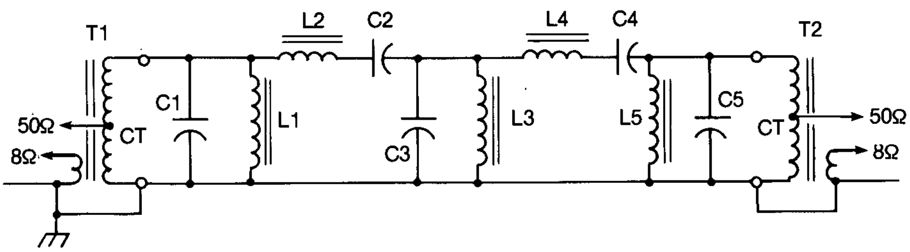
Narrowband Passband Designed for 1-kHz Wobbulated Tone

The BPF is designed for a geometric center frequency of 993 Hz. This particular center frequency is selected so that the higher and lower frequencies of the wobbulated 1-kHz tone may pass through the filter unattenuated. Figure 3 shows the schematic diagram and component values of the narrowband BPF. Standard 8/200-ohm center-tapped transformers provide outputs at either a 50- or 8-ohm impedance level. Figure 4 shows a wiring diagram

FILTER BANDPASS TYPE	CENTER FREQ. (Hz)	C1,C5	C2,C4	C3	L1,L5	L2,L4	L3	Rt Design (ohms)	6-dB BW (Hz)	6-dB Freqs. Low (Hz)	High	R.C. (%)	Applicable Figure Numbers
		---------(μF)---------			--------(mH)--------								
Narrow	993	0.292	1.036	0.0973	88.0	24.8	264	230	305	852	1157	0.0441	2 & 3
Wide	1031	0.271	1.084	0.542	88.0	22.0	44.0	224	2860	340	3200	6.3	4 & 5

NOTES:
1. Rt is the design impedance of the filter. The actual source and load impedances seen by the filter should be within ten percent of the design value.
2. Both bandpass filters can be matched to an 8-ohm source and load using the MOUSER 42TU200, 8/200-ohm center-tapped transformer. To match the filter to a 50-ohm detection system, use the transformer center tap of the high-impedance winding. The wideband filter may also be matched to a 50-ohm detection system without the transformers by using the center taps of inductors L1 and L5.
3. R.C. is the reflection coefficient of the Chebyshev lowpass prototype upon which the bandpass filter designs are based.
4. In the narrowband design, L2 and L4 are obtained by removing turns from a 44-mH inductor. See Appendix E for an explanation of how to determine the number of turns to remove and the proper lead connections.
5. In the narrowband design, three 88-mH inductors in the 5-inductor stack are series connected to get L3. In the wideband design, the windings of two inductors are connected in parallel-aiding to make each inductor 22 mH. The two 22-mH inductors are then connected in series to make the 44-mH L3 value.

Table 1. Component Values and Calculated Design Parameters of Narrowband and Wideband 5-Resonator Bandpass Filters.



C1, C5—0.271 μF
C2, C4—1.084 μF
C3—0.542 μF
L1, L5—88.0 mH
L2, L4—22.0 mH
L3—44.0 mH (See text for wiring details on L2, L4 and L3.)
T1, T2—transformer, 8/200-ohm, ct. 0.4-watt (Mouser 42TU200)
All capacitors are 100-V metallized Mylar. If necessary, two capacitors may be paralleled to obtain the design values within one percent.

Figure 5. Schematic diagram of the wideband bandpass filter. All L-C circuits are resonated at 1031 Hz. C3 can be obtained with paralleled .39-μF and .15μF capacitors. Figure 6 shows the wiring diagram of the filter.

of the narrowband BPF. Figure 5 shows the schematic diagram of the wideband (330-3000 Hz) speech BPF, and Figure 6 shows the wiring diagram. The relative attenuation responses of these two filters are shown in Figure 7. Table 1 lists the component values and design parameters of the narrowband and wideband BPFs. Appendices A and B give the derivation and calculations associated with the design of the narrowband and broadband filters.

BANDPASS FILTERS FOR NON-TUNABLE TESTING

A commonly used test specification requires non-tunable testing using BPFs to define the non-tunable bandwidths where the 6-dB bandwidths are dependent on the data rate of the test signal. A data rate as low as 300 b/s is frequently used when testing PCs in the serial input/output mode. Thus the lower cutoff frequency can be as low as 150 Hz. The upper cutoff frequency of the first non-tunable segment can be as high as 1500 Hz. Additional higher-frequency bandpass segments are used up to a maximum frequency determined by the rise and fall times of the test signal. BPFs for the first and second segments are usually the most difficult to construct because the inductance values are not feasibly hand wound. However, the following discussion will demonstrate how the load coil stacks can be used in the design and how BPFs suitable for the first and second segments of non-tunable detection system can be constructed. Figure 8 shows a typical BPF for non-tunable testing installed in an aluminum box. The five-resonator BPF design is used again since it is eminently suitable for the same reasons given for the speech BPFs. Figure 9 shows the general schematic diagram of two BPFs suitable for non-tunable testing, and Figure 10 shows the corresponding wiring diagram.

300/600-b/s Data Rates

For the first non-tunable segment for data rates of either 300 or 600 b/s, the (A) input/output connection shown in Figures 9 and 10 is used. Table 2 gives the component values and calculated parameters of the 300/600-b/s BPF. Inductors L1 and L5 (41.1 mH) are obtained by modifying a standard 44-mH inductor in accordance with the procedure explained in Appendix E. Specifically, to achieve the 41.1-mH value, seven turns are removed from each winding of the 44-mH inductor, or the total turns removed amount to 14. Using the equation given in paragraph (6) of Appendix E, the calculated total of turns to be removed is 15; but since only an even number can be removed (half of the total from each winding), a total of 14 turns is chosen. Figure 11 (Curve A) shows the measured relative attenuation response of the BPF. The insertion loss at 454 Hz is about 0.5 dB. Although the calculated 6-dB low cutoff frequency of this BPF is 145.4 Hz, the measured cutoff frequency is slightly higher (just below 150 Hz) because of the limited inductor Q. Despite this measurement, the BPF performance still meets all the requirements of the applicable test specification. Appendix C explains the procedure used in calculating the parameters of the 300/600-b/s BPF.

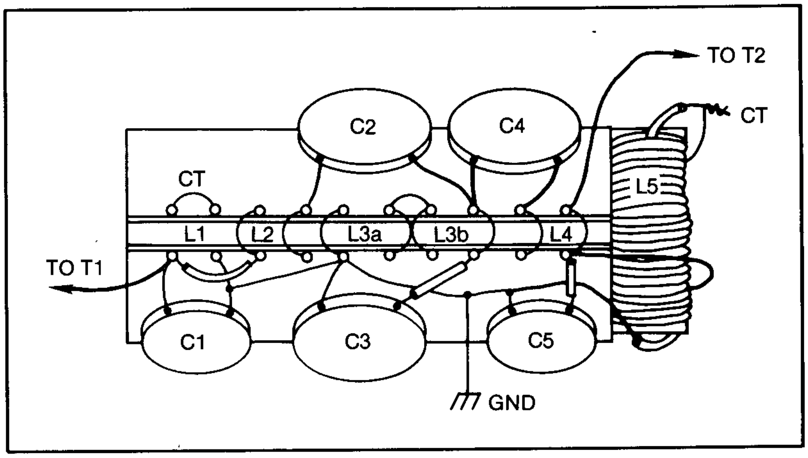


Figure 6. The pictorial diagram shows how to wire the 88-mH inductor stack for the speech filter. L3a and L3b are each 22 mH and are connected in series to make 44 mH. L5 is fastened to the end of the stack with silicone sealer. The center-tap connection of L5 is not used in this application.

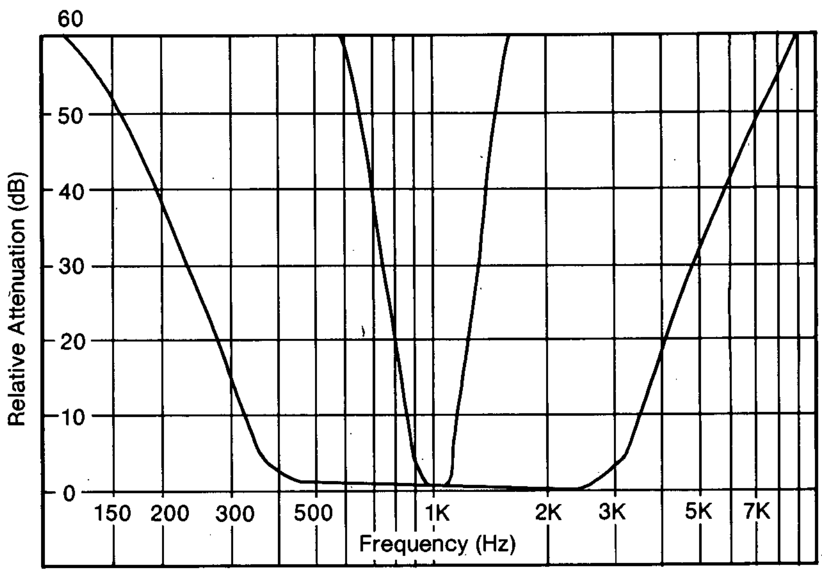


Figure 7. The Measured Relative Attenuation Response of the Narrowband and Wideband Bandpass Filters. The attenuation levels were measured relative to zero dB at the center frequencies of 993 and 1031 Hz, respectively. Table 1 gives the calculated design parameters.

Data Rate (b/s)	Bandwidths Ap	6 dB	Center Freq. (Hz)	6-dB Freq. Low	Hi	C1,5	C2,4 (μF)	C3	R (ohms)
300, 600	998.165	1274.66	454.4	145.4	1420	2.984	11.25	5.632	50
1200, 2400	3992.7	5098.6	1817.5	581.6	5680	.1865	.7034	.3520	200*

*(See Note 1 below)

NOTES:

1. The 1200/2400-b/s 200-ohm design is used as a 50-ohm filter by connecting the input and output leads to the center taps of L1 and L5.
2. The following standard inductor values are used in both filter designs given in Table 2: L1,5 = 41.1 mH (with center taps), L2,4 = 10.9 mH and L3 = 21.8 mH.
3. Figure 9 illustrates the schematic diagrams. Figure 10 diagrams the wiring of the capacitor leads to the inductor stack terminals.
4. A nine-percent reflection coefficient was selected for both filters to give maximum skirt selectivity and a VSWR of less than 1.20.

Table 2. Component values and calculated parameters of 50-ohm, 5-resonator bandpass filters for R.C. = 9 percent. Suitable for first segment non-tunable testing.

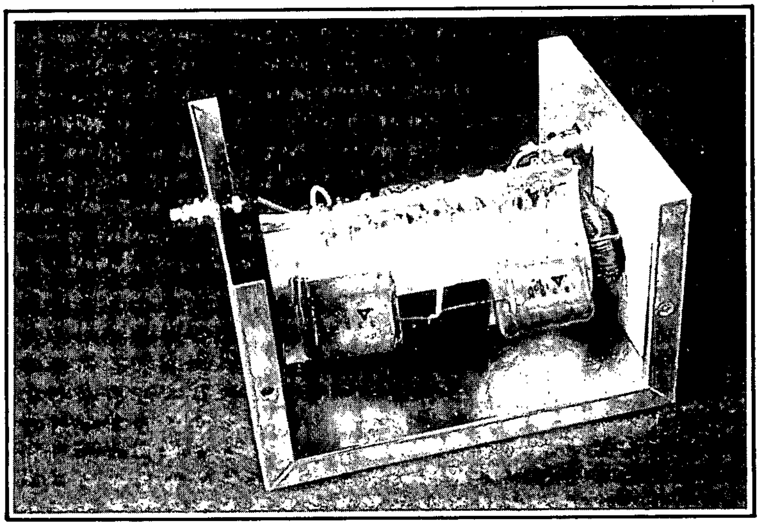
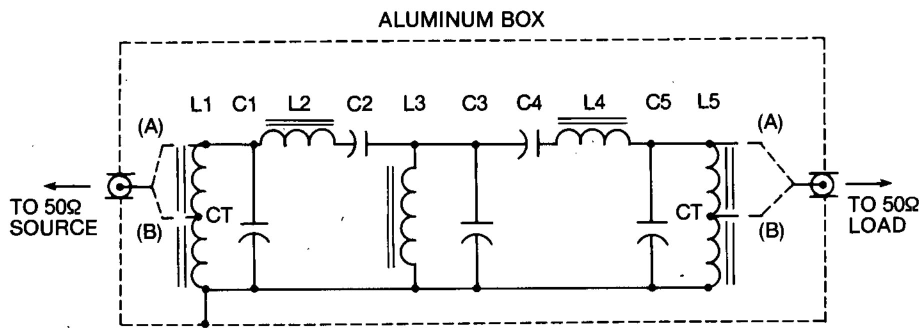


Figure 8. The Bandpass Filter for Non-tunable Testing Installed in a 3 x 4 x 5-inch Aluminum Box. The stack is fastened to the bottom of the box with a plastic mounting clip, and the modified 44-mH inductors are secured to each end of the inductor stack with silicone sealer. Figures 9 and 10 show the schematic and wiring diagrams.



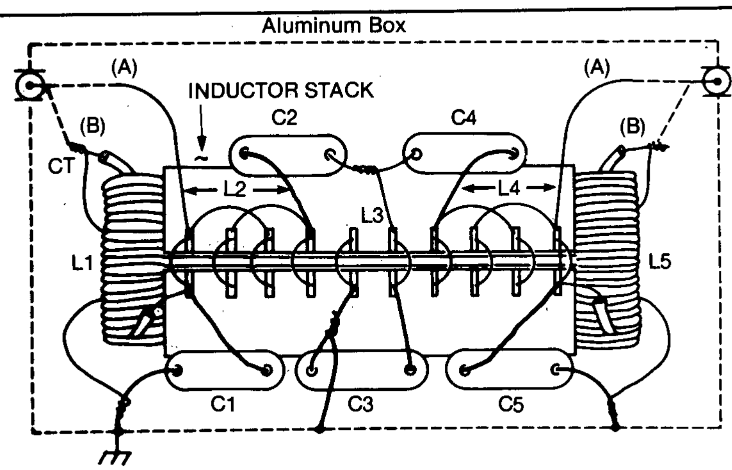
NOTES:

1. For the 300/600-b/s data rate bandpass filter, use the corresponding component values in Table 2 and the "(A)" input/output connection shown above. For example, C1 and C5 = 2.984 μF.
2. For the 1200/2400-b/s data rate bandpass filter, use the corresponding component values in Table 2 and the "(B')) input/output connection shown above. For example, C1 and C5 = 0.1865 μF.

Figure 9. Schematic diagram of the bandpass filters for nontunable testing. See Table 2 for the component values and calculated performance parameters.

1200/2400-b/s Data Rates

The 1200/2400-b/s BPF is designed for a 200-ohm impedance level (Table 2) so that the same inductor values used in the 300/600-b/s design can be used again. Table 2 gives the new capacitor values for this design. Only the input/output connections and the capacitor values change. The 50-ohm input/output connections are obtained by using the center-tap on inductors L1 and L5. The calculated 6-dB cutoff frequencies of this BPF indicate that it may be used as a second segment filter when performing the non-tunable tests for 300/600-b/s data rates. The insertion loss of this BPF is about 0.5 dB, and the measured relative attenuation is shown by curve (B) in Figure 11. Because of imperfect coupling in the windings of L1 and L5, the center-tap connection does not function as well as it should, and causes the filter passband to have a ripple of about 0.5 dB. The measured upper 6-dB cutoff frequency exceeds ten times the lower 6-dB cutoff frequency by about six percent, but this minor discrepancy from the test specification should not prevent the filter from being used. For the non-tunable segments above 5 kHz, standard lowpass and highpass decade filters may be cascaded.



NOTES:

1. Use the input/output connection "(A)" for wiring the bandpass filter for the 300/600-b/s data rate testing. Use the input/output connection "(B)" for wiring the bandpass filter for the 1200/2400-b/s data rate testing.
2. See Figure 9 for the schematic diagram of the two filter types.

Figure 10. The pictorial diagram shows the wiring of the bandpass filters for nontunable testing.

SUMMARY

Bandpass filters are required when performing tests in accordance with certain test specifications. Previously, passive LC filters for the low-frequency audio range were not practical for construction by the test technician because of the more than two hundred turns required for the inductors. This article explains a new design and construction procedure in which surplus load coil stacks are used as the inductor elements thereby eliminating the need to wind inductors. Design and construction examples are given for bandpass filters useful in testing analog speech communication systems and in performing first and second segment non-tunable tests for the 300/600 and 1200/2400-b/s data rates used in the serial I/O ports of personal computers. Appendices provide examples of the design procedures so that different bandpass filters may be developed by the interested reader. ■

REFERENCES

1. Wetherhold E. "Inductance and Q of Toroidal Inductors," QST, Sept. 1968.
2. 1989 ARRL Handbook for the Radio Amateur. 66th ed., Newington: The American Radio Relay League, 1988.
3. Orr, William, ed. Handbook for the Radio Amateur. 21st ed. Indianapolis: Howard W. Sams & Co., 1987.
4. Wetherhold E. "CW and SSB Audio Filters Using 88-mH Inductors," QEX, Dec. 1988.

- *Typetronics, Box 8873, Ft. Lauderdale, FL 33310. Send SASE for details.*
- *Amidon Associates, 12033 Otsego St., North Hollywood, CA 91607. Request "Iron-Powder and Ferrite Coil Forms" data sheet and price list.*
- *E. Wetherhold, 1426 Catlyn Place, Annapolis, MD 21401. Send SASE for details.*

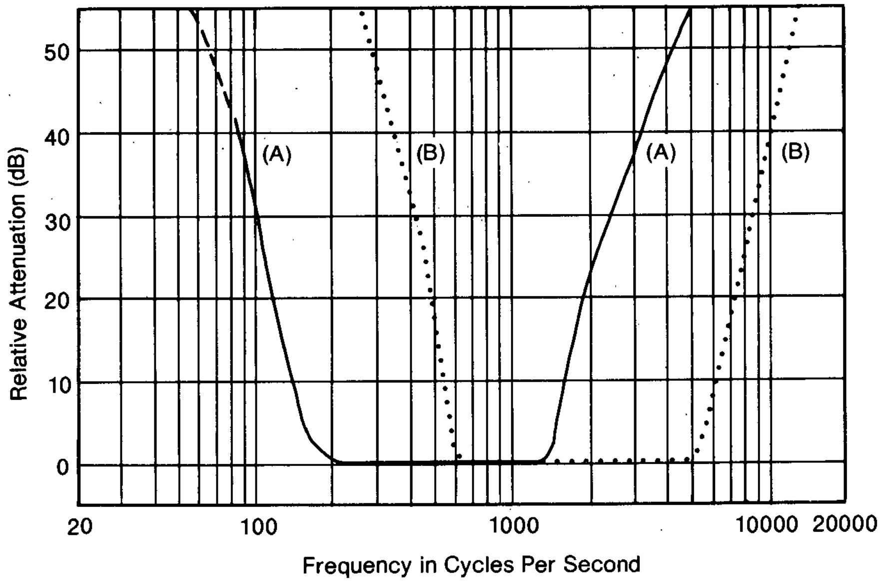


Figure 11. The Measured Relative Attenuation Responses of the Bandpass Filters for Non-tunable Testing. The attenuation levels were measured relative to zero dB at the center frequencies listed in Table 2.

APPENDIX A

Derivation and Calculation of Narrowband Bandpass Filter Element Values and Parameters

Derivation and Calculation of Narrowband Bandpass Filter Element Values and Parameters

```
       o--XXXXX---+---XXXXX---+---XXXXX--o
                  |           |
Rt <--          -----       -----        --> Rt
                -----       -----
       o----------+-----------+----------o
             1    2     3     4     5
```

Figure A1. The inductor-in/out configuration is used for the narrowband bandpass filter design. The numbered components are listed in Table A1 with their normalized values.

Reflection Coeff. (%)	G1, 5 (H)	G2, 4 (F)	G 3 (H)	G3/G1 Ratio
0.0441	0.1054	0.2625	0.3162	3.000
6.30	0.1642	0.2657	0.3284	2.000

Table A1. The Chebyshev component values (G1-5) are normalized for one-ohm terminations and for a 3-dB cutoff frequency of one hertz.

The steps in the derivation procedure follow:

(1) Assume the filter termination impedance (Rt) will be the sum of an 8-to-200-ohm transformed impedance, the transformer winding resistances transferred to the high-Z winding plus the L1,5 inductor resistance, or a total of about 230 ohms. Also, assume the design Rt will be 4*230 = 920 ohms, and inductors L1,5 will be 4*88 = 352 mH.

(2) For a narrowband (NB) design, use the normalized values for RC = .0441% where L3 = 3*L1, and where L1 = 352 mH. For a design with a BW 1.6 times greater, use the normalized values for RC = 6.3%. The calculations for a NB design follow.

(3) Calculate the 3-dB bandwidth (B3) based on Rt= 920 ohms, L1= .352 H and G1 = .1054 H:

B3 = G1*Rt/L1 = .1054*920/.352 = 275.5 Hz.

Because of inductor losses, the actual 3-dB bandwidth will be about eight percent narrower than the calculated B3.

(4) Find C2,4 based on B3 = 275.5 Hz:
C2 = G2/(Rt * B3) = .2625/(920*275.5) = 1.0357 uF.

Summarizing the lowpass design values: L1,5 = 0.352 H, L3 = 1.056 H, C2,4 = 1.0357 uF, Rt = 920 ohms and B3 = 275.5 Hz. This lowpass design will be transformed into a bandpass (BP) filter having a center frequency (Fc) selected by the designer. Figure A2 shows the BP filter schematic diagram.

```
o---][---XXX---+---+---][--XXX---+---+---XXX---][---o
               ¦   ¦             ¦   ¦
(-- 920       ---  X             X  ---         920 --)
   ohms       ---  X             X  ---         ohms
               ¦   X             X   ¦
o--------------+---+-------------+---+--------------o
    - 1 -     - 2 -    - 3 -    - 4 -    - 5 -
```

Figure A2. Bandpass filter schematic diagram.

(5) Assume that Fc is to be 993 Hz. Calculate L2 based on C2 = 1.0357 uF where L2, C2 and Fc are in mH, uF and kHz:
L2=25.33/[C2*(Fc^2)] = 25.33/[(1.0357 * (.993^2)] = 24.8 mH.
L2 & L4 are obtained by removing about 28% of the turns from a 44-mH inductor. See article text for details. Because L2,4 can be varied, the Fc can be between 500 and 1500 Hz.

(6) The relative percentage bandwidth (%BW) = 100*B3/Fc = 275/9.93 = 27.7%. The minimum Q required to obtain a close approximation of the calculated response is: Qmin = 20*Fc/B3 = 72. Because inductor Q at 1kHz is only about 50, the difference between the actual and calculated responses will be noticeable. In spite of this, an inductor Q of 50 at 1kHz will be adequate for this application.

(7) C1,5 and C3 are calculated based on L1 and L5 =352 mH, L3 = 1056 mH and Fc = .993 kHz:

C1 = 25.33/[L1*(Fc^2)] = 0.0729783 uF,
C3 = (C1)/3 = 0.0729783/3 = 0.024326 uF.

Summarizing all values calculated so far:

```
C1,5 = 0.07298 uF    L1,5 = 352 mH     B3 = 275.5 Hz
C2,4 = 1.0357  uF    L2,4 = 24.80 mH   Fc = 993 Hz
  C3 = 0.02433 uF      L3 = 1056 mH    Rt = 920 ohms
```

All LC products = 25.69 * 10^-9 to give Fc = 993 Hz.

(8) The three series branches are moved to the L2 and L4 center taps. The series-branch reactances become 1/4th of their former values. The L1,3 and 5 values are quartered and the C1,3 and 5 values are quadrupled. C2,4 and L2,4 remain unchanged. The L1,3 and 5 values now can be realized with one or more 88-mH inductors. Rt becomes 230 ohms. Figure A3 shows the final diagram and component values.

```
                  +---+             +---+
     C1   L1      X   ¦   C3  L3    X   ¦    L5   C5
o---][---XXX---X---)---][--XXX---X---)---XXX---][---o
                  X   ¦             X   ¦
(- 230 ohms   L2 ¦   ---        L4 ¦   ---       230 ohms-)
                 ¦   --- C2        ¦   --- C4
o----------------+---+-------------+---+----------------o

C1,5 = 0.292  uF,     L1,5 = 88.0 mH,     B3 = 275 Hz
C2,4 = 1.036  uF,     L2,4 = 24.8 mH,     Fc = 993 Hz
  C3 = 0.0973 uF,       L3 = 264  mH,     Rt = 230 ohms
```

Figure A3. Schematic diagram and component values of the bandpass filter with F-center = 993 Hz and Rt = 230 ohms.

APPENDIX B

Derivation and Calculations of Wideband Filter Element Values and Parameters

```
         o---+---XXXXX---+---XXXXX---+---o
             ¦           ¦           ¦
Rt (--     -----       -----       -----  --) Rt
           -----       -----       -----
             ¦           ¦           ¦
         o---+-----------+-----------+---o
             1     2     3     4     5
```

The components are numbered 1 to 5, left to right. G1,5 = .1642F, G3 = .3284F, G2,4 = .2657H, G3/G1 = 2.000. Rt= one ohm and the reflection coefficient = 6.3 percent.

Figure B1. The filter schematic is shown with the normalized component values (G1-5) of the lowpass prototype used in designing the wide bandpass filter. The component values are normalized for one-ohm terminations and for a 3-dB cutoff frequency of one hertz. A reflection coefficient of 6.3 percent was selected so that G3 is twice as large as G1.

The steps in the derivation procedure follow:

(1) L2 and L4 must be 22 mH to allow use of a standard

inductor value. Rt is to be 224 ohms so an 8/200-ohm transformer (MOUSER 42TU200) can be used. The exact Rt value is based on an 8-ohm source transformed to 200 ohms plus the transformer winding resistances referred to the high impedance winding (200 + 12 + 12 = 224 ohms).

Find the 3-dB bandwidth (B3) of the desired bandpass filter based on the lowpass prototype in Figure B1:

B3 = Rt*G2/L2 = 224 * .2657/.022 = 2705.3 Hz.

(2) Calculate C1 & C3 for a 3-dB bandwidth of 2705.3 Hz:

C1,5 = G1/(Rt * B3) = .1642/(224 * 2705.3)
= 0.27096 uF.

C3 = 2 * C1 = 2 * .27096 uF = .5419 uF.

(3) Transform the lowpass prototype in Figure B1 into a bandpass design by resonating all components to Fc. See Figure B2 for the bandpass schematic diagram.

```
     o---+----+--][--XXX--+-----+--][--XXX---+----+---o
(--      |    |           |     |            |    |  --)
Rt =    ---   X          ---    X           ---   X  Rt =
224     ---   X          ---    X           ---   X  224
ohms     |    X           |     X            |    X  ohms
         |    |           |     |            |    |
     o---+----+-----------+-----+------------+----+---o
        - 1 -  - 2 -     - 3 -    - 4 -      - 5 -
```

Figure B2. Bandpass filter schematic diagram.

(4) Calculate the bandpass center frequency which is to be based on the values of C1 and L1. C1 has already been determined. L1 must be 88 mH to allow use of a standard inductor value that gives an Fc near the center of the desired wide bandpass filter. Since the desired 3-dB lower and upper frequencies are about 300 and 3000 Hz, Fc should be within 10% of SQR(300*3000) = 950 Hz. Calculate the actual value of Fc by using the values of C1 and L1:

Fc = 159.155/SQR(L1 * C1) where Fc is in Hz and L1 and C1 are in H and uF. L1 = .088 H and C1 = .27096 uF.

Fc = 159.155/.1544166 = 1030.686 = 1030.7 Hz.

(5) Calculate L3: L3 = (L1)/2 = .088/2 = 44 mH.

(6) Based on the 3-dB bandwidth (B3) and Fc, calculate the lower and upper 3-dB frequencies, F3L and F3U:

F3L = SQR(Fc^2 + X^2) - X, where X = B3/2 = 1352.65 Hz,
F3L = SQR(1030.7^2 + 1352.65^2) - 1352.65 = 347.94 Hz.

F3U = F3L + B3 = 347.94 + 2705.3 = 3053.2 Hz.

As a check, Fc=SQR(F3L*F3U) =SQR(347.94*3053.2)= 1030.7 Hz.

Reviewing the calculated design parameters, it is seen that the Fc, B3, F3L and F3U values for the wide BP filter application are satisfactory, and the design is acceptable. If not, the Rt value of 224 ohms may be varied within ten percent to obtain slightly different parameter values.

The relative percentage bandwidth is BW% = 100*B3/Fc = 262.5%. The minimum required inductor Q to obtain a close approximation of the ideal response is Qmin =20*Fc/B3 =7.6. The results of these calculations indicate that there should be no difficulty in using the 88/22-mH inductors to obtain a bandpass response that closely approximates the ideal response since the inductor Q at 1000 Hz is about 50. Only when a relative bandwidth of less than about 20% is required will the actual bandpass response be significantly less than ideal because of limited inductor Q.

(7) Calculate C2 & C4 based on L2= 22 mH and the Fc value where C2, L2 and Fc are in uF, mH and kHz, respectively:

C2,4 = 25.33/(L2 * Fc^2),
= 25.33/(22 * 1.0307^2)= 25.33/23.3715 = 1.0838 uF.

NOTE: All circuits are tuned to Fc = 1030.7 and all tuned circuits have an LC product of 23.84 * 10^-9.

This concludes the derivation of the BP filter design procedure. By using other Rt values that can be matched with standard transformers (such as 8/500 or 8/1000 ohms), other distinctly different bandwidths may be obtained.

APPENDIX C

Procedure for Calculating the Parameters of a Bandpass Filter Suitable for Non-tunable Testing at Data Rates of 300 and 600 b/s

1. From Table D1, the 50-ohm, 1-Hz normalized component values for R.C. = 9% are selected: G1,5 = 2979 uF, G2,4 = 10.88 H and G3 = 5621 uF. This design is used so the calculated 6-dB low frequency of the bandpass filter will be less than 150 Hz and the VSWR will be less than 1.20.

2. The lowpass filter configuration to be used is shown below:

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```
           C1    L2    C3     L4    C5
       o----+---XXXX---+---XXXX--+----o
            |          |         |
 50 <---   ---        ---       ---   ---> 50
           ---        ---       ---
            |          |         |
       o----+----------+---------+----o
```

L2 and L4 must be 10.9 mH so each can be derived from two parallel-connected 21.8 mH inductors that are in the standard 88-mH inductor stack.

3. Find the ripple bandwidth, BAp, of the lowpass filter shown above, which will be transformed into a bandpass filter having the same ripple bandwidth:

BAp(Hz) = G2/L2 = 10.88/.0109 = 998.165 Hz.

Find the 6-dB and 20-dB bandwidths, B6 and B20, where the 6-dB and 20-dB normalized bandwidths (from Table D2, RC=9%) are 1.277 and 1.641, respectively:

B6 = 1.277 * 998 = 1275 Hz, B20 = 1.641 * 998 = 1638 Hz.

4. Calculate C1 = G1/BAp = 2979uF/998.165 = 2.9845 uF,
and C3 = G3/BAp = 5621uF/998.165 = 5.6313 uF.

5. Let L3 = 21.8 mH so one standard-value inductor can be used.
Find F-center based on the assumed value of L3 and the calculated value of C3:

Fc = 159.2/SQR(L3*C3) = 159.2/SQR(.0218*5.6313) = 454.4 Hz.

6. Calculate L1 and C2 for Fc = .4544 kHz, C1 = 2.9845 uF and L2 = 10.9 mH:

L1 = 25.33/(C1*Fc^2) = 25.33/(2.9845*(.4544^2)) = 41.1 mH,
C2 = 25.33/(L2*Fc^2) = 25.33/(10.9*(.4544^2)) = 11.25 uF.

7. Find the lower and upper ripple cutoff frequencies and the 6-dB and 20-dB frequencies on the bandpass response curve using the BAp, the B6 and the B20 values from (3) above:

(a) FApLO= -BAp/2 +SQR[(BAp/2)^2 +(Fc)^2]= -499.1 +SQR[499.1^2 +454.4^2]=175.9 Hz,
FApUP= FApLO + BAp = 175.9 + 998.165 = 1174 Hz.

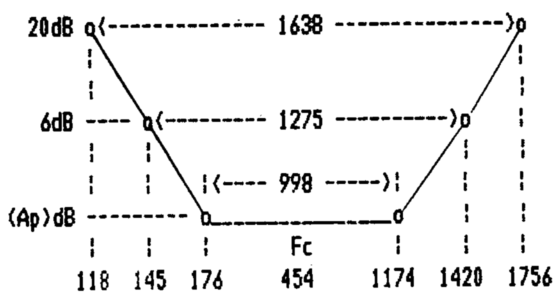
(b) F6LO = -B6/2 +SQR[(B6/2)^2 +(Fc)^2] = -637.5 +SQR(637.5^2 +454.4^2)=145.4 Hz,
F6UP = F6LO + B6 = 145.4 + 1275 = 1420 Hz.

(c) In a similar manner, calculate F20LO = 117.6 Hz and F20UP = 1756 Hz.

8. The schematic diagram and response curve of the bandpass filter are shown below:

```
           C2   L2            C4   L4
   o--+---+-||-XXXXXX-+---+-||-XXXXXX-+---+--o
      |   |           |   |           |   |
 <-- ---  X          ---  X           X  --- -->
 50  ---  X          ---  X           X  --- 50
      |   |           |   |           |   |
   o--+---+-----------+---+-----------+---+--o
     C1   L1         C3   L3         L5   C5
```

(A) Schematic diagram



(B) Calculated attenuation response

APPENDIX D

Normalized Parameters of 5th-order Chebyshev Lowpass Filters for Reflection Coefficients of 1 to 12 Percent

Table D1. 5th-Order Chebyshev lowpass filters normalized for a one hertz ripple cutoff frequency and 50-ohm terminations.

R.C. (%)	VSWR -----	Ap (dB)	F3/F-Ap Ratio	G1,G5 (uF)	G2,G4 (H)	G3 (uF)	G3/G1 RATIO
1.0	1.020	.000434	1.6160	1550	8.353	3901	2.517
2.0	1.041	.001738	1.4549	1861	9.305	4358	2.341
3.0	1.062	.003910	1.3739	2088	9.837	4649	2.227
4.0	1.083	.006954	1.3218	2275	10.19	4872	2.141
5.0	1.105	.010871	1.2844	2440	10.43	5056	2.073
6.0	1.128	.015663	1.2558	2589	10.60	5217	2.016
6.3	1.134	.017272	1.2484	2631	10.64	5262	2.000
7.0	1.151	.021333	1.2328	2726	10.73	5362	1.967
8.0	1.174	.027884	1.2138	2856	10.82	5496	1.924
9.0	1.198	.035321	1.1978	2979	10.88	5621	1.887
10.0	1.222	.043648	1.1840	3098	10.92	5740	1.853
11.0	1.247	.052870	1.1719	3212	10.94	5854	1.822
12.0	1.273	.062993	1.1612	3323	10.95	5964	1.795

Table D2. Frequencies vs. stopband attenuation of 5th-order Chebyshev lowpass filters normalized for a ripple cutoff frequency of one hertz.

	Attenuation Levels (dB)							
R.C.	1.0	3.01	6.0	10	20	30	40	50
(%)	Normalized Frequencies							
1.0	1.459	1.616	1.765	1.936	2.394	2.965	3.693	4.617
2.0	1.325	1.455	1.579	1.724	2.114	2.605	3.234	4.034
3.0	1.259	1.374	1.485	1.616	1.970	2.419	2.995	3.730
4.0	1.217	1.322	1.424	1.545	1.875	2.296	2.837	3.529
5.0	1.187	1.284	1.380	1.494	1.806	2.205	2.721	3.381
6.0	1.164	1.256	1.346	1.455	1.752	2.135	2.630	3.265
6.3	1.158	1.248	1.338	1.444	1.738	2.117	2.607	3.235
7.0	1.146	1.233	1.319	1.423	1.709	2.078	2.556	3.171
8.0	1.131	1.214	1.297	1.396	1.672	2.029	2.494	3.091
9.0	1.119	1.198	1.277	1.373	1.641	1.988	2.440	3.023
10.0	1.108	1.184	1.261	1.353	1.613	1.952	2.394	2.963
11.0	1.099	1.172	1.246	1.336	1.589	1.920	2.352	2.909
12.0	1.091	1.161	1.233	1.321	1.568	1.891	2.315	2.862

APPENDIX E

Procedure for Calculating the Number of Turns to Be Removed from a 44-mH Inductor to Get Any Inductance Less than 44 mH

(1) The 44-mH inductor used in the narrowband filter construction has two separate windings on opposite halves of a molybdenum-permalloy core. The polyurethane insulated wires are solderable at 750 to 800 deg. F, and the leads do not need to be scraped to remove the insulation. The soldering fumes are irritating to the lungs and eyes - so keep your face away from the fumes, and solder only in a well-ventilated area.

(2) Measure the original inductance, Lo, with the two windings connected in series-aiding (S-A). To do this, connect the start lead of one winding to the finish lead of the other winding, and connect the other two leads to an inductance bridge. An alternate method of finding the inductance is to resonate the inductor with a known capacitance and calculate the inductance based on the capacitance and resonant frequency. To do this, connect the inductor leads across a nominal 0.47-uF capacitor (previously measured to an accuracy of better than 0.5 percent) and lightly couple an audio generator and an a-c VTVM to the tuned circuit with two 1000-pF capacitors. Vary the generator frequency until the VTVM indicates a voltage peak. Measure the resonant frequency (approx. 1107 Hz) with a digial frequency counter and calculate the inductance with the equation:

Lo = 25.33/[(F^2)*C] where Lo, F and C are in mH, KHz and uF.

(3) Remove 50 turns from each of the two windings (total turns removed = 100) and again connect the windings in series aiding. Measure the new inductance, Lm.

(4) Calculate To = 100*R/(R-1), where R = SQR(Lo/Lm), To = original number of turns on the inductor core, Lo = original inductance in the S-A connection, and Lm = modified inductance after removing a total of 100 turns (50 turns from each winding). "SQR(Lo/Lm)" means "take the square root of (Lo/Lm)."

For example, if Lo = 43.6 mH and Lm = 28.5 mH, then R = 1.236861 and To = 522 turns.

(5) Calculate: S = (To - 100)/SQR(Lm) where Lm is the modified inductance after removing 100 turns from the inductor. For example, if an inductor has Lo = 43.6 mH, To = 522 and Lm = 28.5 mH for 100 turns removed, then:

S = (522 - 100)/SQR(28.5) = 79.0478.

(6) Use the following general equation (applicable to all two separate-winding inductors with Lo = 43.6 mH) to find the number of turns to remove to obtain a specific inductance: Td = To - [S * SQR(Ld)], where Td = total number of turns to remove from an unmodified 43.6-mH inductor, To = total number of original turns on the inductor core, Ld = desired inductance in mH and S is the value calculated in (5). For example, for the values given in (5) and if the desired inductance, Ld, is 24.8 mH, then:

Td = 522 - [79.0478 * SQR(24.8) = 522 - 394 = 128 turns to be removed from the original inductor. Since 100 turns have already been removed, an additional 128-100 = 28 turns must be removed to get 24.8 mH. Because turns must always be removed equally from each winding to maintain balance, an additional 14 turns must be removed from each of the two separate windings.