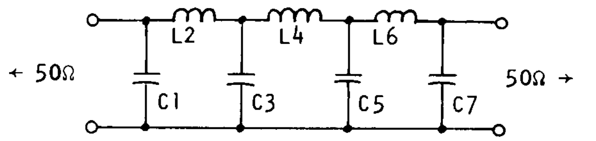
SELECTED CHEBYSHEV FILTERS FOR NARROWBAND NON-TUNABLE TEMPEST TESTING

Introduction

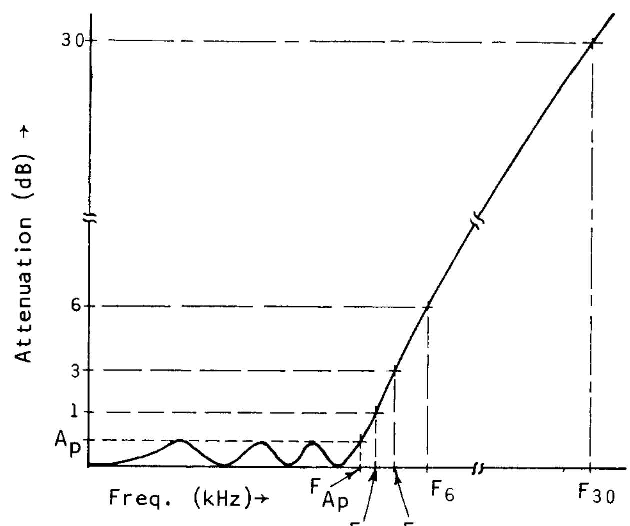
In last year's issue of ITEM[1], the design, construction and performance of twelve Butterworth lowpass filters intended for broadband non-tunable (BB NT) TEMPEST testing were discussed. The designs were especially useful because the filters provided excellent selectivity (due to the use of seven elements), and only standard-value capacitors were required for the filter construction. Because the BB NT TEMPEST test specification requires only three upper cutoff frequencies (1, 10 and 30 MHz) to limit the detection system bandwidth, it was feasible to meet the filtering requirements with the Butterworth filter type. Only two Butterworth designs were needed — one for the 1-MHz bandwidth and another for the 30-MHz bandwidth. The filter for the 10-MHz bandwidth was the same as the 1-MHz design, except its component values and attenuation response were scaled from 1 to 10 MHz. Although only two Butterworth designs were necessary, six 1-MHz and six 30-MHz lowpass filter designs were listed in last year's ITEM article to account for all possible designs that fell within the ±25% window allowed for the 6-dB cutoff frequency.

Because of the advantages of the Butterworth filter type (low VSWR, flat passband response, constant input impedance, little effected by component value variation, adequate selectivity, and ease of design and construction), it would be nice if this type filter could also be used for narrowband (NB) NT TEMPEST testing. This, unfortunately, is not practical because the NB NT detection system bandwidth limits (unlike the BB NT limits) are not fixed but instead are dependent on the data rate of the equipment under test (EUT). Also, highpass filters are needed in addition to the lowpass filters. Since the EUT data rate can be almost any value between 1200 b/s and 1 Mb/s (for example), a large selection of filter designs is necessary to cover one frequency decade. (Designs for the other decades can be determined by a simple scaling process.) Unfortunately, the major shortcoming of the Butterworth design is that only a few filters can be realized from standard-value capacitors. For example, the seven-element capacitor-input/output Butterworth design (see Figures 1A and 2A for the filter configuration under discussion) has a capacitance ration of 4.0489 (C3/C1 for lowpass, and C1/C3 for highpass), and only a few pairs of standard capacitor values closely approximate the exact value. For example, standard-value pairs of .39/.1 and .51/.13 are both within 3.8% of being an exact match for the Butterworth ratio. Because of its fixed capacitor ratio, the Butterworth design is inappropriate for NB NT TEMPEST test applications. A more suitable filter type is one that permits variations in the C3/C1 (or C1/C3) capacitance ratio in exchange for a variation in a performance parameter that is acceptable to the user. The filter type that meets these requirements is the Chebyshev type, and it will be used as the basis for developing a series of thirty lowpass and highpass designs (each having seven elements) covering the 6 kHz to 60 kHz frequency decade. Filters for the higher (and lower) frequency decades can be determined by a simple scaling process.

The capacitor input/output configuration was selected instead of the alternate inductor input/output configuration to minimize the number of inductors. The 7-element filter was chosen instead of the 5-element filter because of its greater selectivity and because there is little difficulty in obtaining the additional two elements. In the 7-element filters shown in Figures 1 and 2, C1 = C7, C3 = C5 and L2 = L6. Because two can be ordered just as easily as one, there is no problem in obtaining the additional capacitor. An additional inductor having a value different from the other two is also required, but this presents no problem as all the inductors are easily hand-wound on the same type core to provide any inductance value that may be needed. Thus, for a small additional effort over that used in constructing a 5-element filter, it is possible to make a 7-element filter having an additional 12 dB/octave or more of attenuation as compared to the 5-element filter. For these reasons, the 7-element lowpass and highpass Chebyshev filters are considered to be an optimum design choice for NB NT TEMPEST test applications.

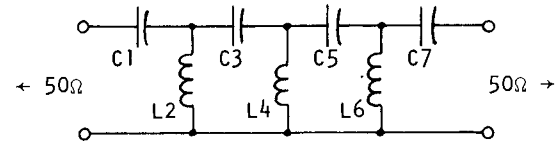


(A) Schematic Diagram

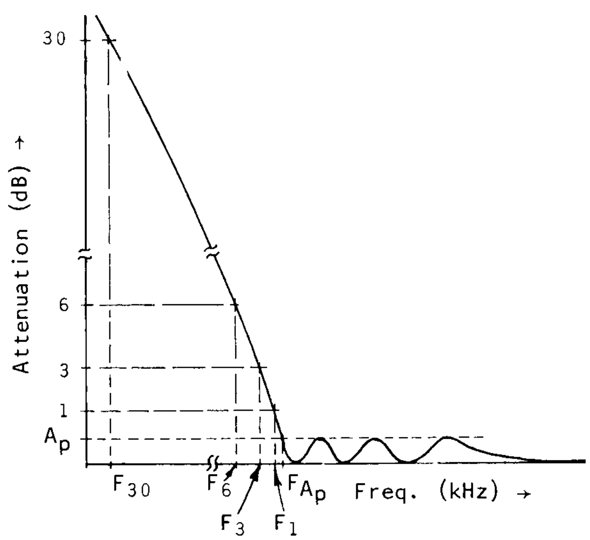


(B) Typical Attenuation Response

Figure 1. Lowpass Filter Schematic Diagram and Response



(A) Schematic Diagram



(B) Typical Attenuation Response

Figure 2. Highpass Filter Schematic Diagram and Response

Recommended Chebyshev Filters for TEMPEST Testing

Table 1 lists thirty-five 50-ohm lowpass filters with 3-dB cutoff frequencies from about 6 kHz to 84 kHz. Actually, there are only thirty distinctly different designs, since the last five designs (#31 to 35) are the first five designs scaled into the next higher frequency decade. (Note the identical values of RC and VSWR between the first and last five designs, and how the frequency and component values differ by a factor of ten and one-tenth, respectively.) This was done to provide examples of the effects of frequency scaling.

The first column of Table 1 identifies each design with a number for easy reference. The next five columns list frequencies in kilohertz that correspond to the attenuation levels at the top of the column. Using this data, it is possible to roughly plot the attenuation response of all filters. The "F-AP" column gives the frequency where the attenuation first exceeds the peak level of the passband attenuation ripple (see Figure 1B). This value is used in the calculation of the other listed frequencies and of the component values. The 1-dB frequency is listed because it is good to know when the filter attenuation begins to become significant. The 3-dB frequency is listed because it is a commonly used reference level in filter design, and the 6-dB frequency is listed because the TEMPEST test specifications use this frequency in defining the cutoff frequency of the filter response roll-off. The 30-dB frequency was arbitrarily selected as an indication of the filter stopband performance.

The next column, R.C. (%), lists the reflection coefficient (RC) of a specific Chebyshev filter design having the listed parameters for the given F-AP value. Knowing the RC, it is possible to calculate the normalized element values of the filter. Both the RC and F-AP values define a specific filter design having the listed standard capacitor values. The RC value is of primary interest to the filter designer, and it is included mainly for reference purposes.

The VSWR listing is of interest to the filter user as it gives an indication of the maximum variation that occurs to the filter input impedance when the other end of the filter is terminated in 50 ohms. The highest listed VSWR is 1.148. Filters with relatively low VSWR levels were selected to minimize filter input impedance changes and to make the designs less susceptible to component value variations. Even though the listed designs do not have a wide range of VSWR levels, there are a sufficient number of different Chebyshev designs between VSWR values of 1.000 (corresponding to a Butterworth design) and the maximum value of 1.148, so a considerable number of different filters can be realized with the limited number of standard capacitor values that are available. It is the VSWR (or RC) design parameter that is allowed to vary in order to obtain many different C3/C1 ratios so that a large number of different filters can be realized with standard-value capacitors. From a construction standpoint, this is the main advantage of the Chebyshev design as compared to the Butterworth. Because the Ap attenuation level is insignificant in this particular application, it is not listed. For example, the Ap level corresponding to a RC of 6.874% (VSWR = 1.16) is less than .021 dB, which is undetectable. The Ap level shown in Figure 1B is greatly exaggerated for ease in depicting this parameter.

The last four columns of Table 1 are the capacitor and inductor component values of the filter. Looking down column C1,7, the commonly available standard values associated with the ±10% tolerance series are noted. The C3,5 column lists the standard values associated with the 5% tolerance series. Of course, many more designs could have been tabulated if the 5% values were also included in the C1,7 column, but the thirty different designs provided were adequate to cover the frequency decade, thus making additional designs unncessary. The inductor values of L2, L6 and L4 are any miscellaneous value that results from C1,7 and C3,5 forced to be a standard value. However, as a coincidence, design #5 has inductor values that are essentially standard 1.5 and 1.8 mH values. In this instance, this design can be realized with standard catalog values for both capacitors and inductors. No additional effort was expended in finding filter designs having standard inductance values because these components can be hand-wound to the individual requirements of each design. Of course, this is not possible with the capacitors, and the filter constructor is therefore dependent on the capacitor manufacturer for providing this component.

Table 2 lists thirty-five 50-ohm highpass filters, and the explanation of the column headings and various parameters previously discussed for the lowpass filters is also applicable to the highpass filters. Note that the highpass and lowpass capacitors values are identical in those designs having identical R.C. and VSWR values, except the C1,7 and C3,5 values are exchanged. As might be expected, the highpass frequency and inductance values are quite difference from the lowpass values.

Table 1.

Lowpass 50-ohm 7-Element Chebyshev Filters,

Design Parameters and Component Values

FLTR NO.	FREQUENCY AT AP, 1, 3, 6 & 30 DB (KILOHERTZ) F-AP	F-1DB	F-3DB	F-6DB	F-30DB	R.C. (%)	VSWR (MAX.)	C1,7 (UF)	C3,5 (UF)	L2,6 (UH)	L4 (UH)
1.	4.15	5.58	5.97	6.33	8.9	.353	1.007	.33	1.00	1966.	2624.
2.	5.69	6.18	6.44	6.70	8.8	5.730	1.122	.47	1.00	1969.	2288.
3.	5.08	6.26	6.65	7.01	9.7	.925	1.019	.33	.91	1830.	2337.
4.	6.17	7.14	7.52	7.88	10.7	2.130	1.044	.33	.82	1664.	2038.
5.	7.22	8.03	8.40	8.77	11.7	3.860	1.080	.33	.75	1508.	1789.
6.	5.94	8.18	8.76	9.29	13.2	.278	1.006	.22	.68	1329.	1791.
7.	8.58	9.22	9.60	9.96	13.0	6.874	1.148	.33	.68	1319.	1518.
8.	7.29	9.15	9.73	10.26	14.2	.755	1.015	.22	.62	1241.	1601.
9.	8.86	10.38	10.95	11.49	15.6	1.782	1.036	.22	.56	1136.	1404.
10.	10.47	11.72	12.29	12.83	17.1	3.410	1.071	.22	.51	1029.	1229.
11.	8.42	11.80	12.65	13.43	19.1	.233	1.005	.15	.47	914.	1241.
12.	12.08	13.13	13.69	14.23	18.7	5.600	1.119	.22	.47	927.	1078.
13.	10.32	13.14	13.99	14.77	20.6	.640	1.013	.15	.43	858.	1115.
14.	12.50	14.83	15.67	16.46	22.5	1.514	1.031	.15	.39	790.	985.
15.	14.44	16.43	17.26	18.05	24.3	2.710	1.056	.15	.36	729.	882.
16.	10.94	16.61	17.90	19.07	27.4	.108	1.002	.10	.33	630.	880.
17.	16.82	18.47	19.29	20.09	26.5	4.710	1.099	.15	.33	658.	772.
18.	14.02	18.65	19.93	21.10	29.7	.397	1.008	.10	.30	591.	785.
19.	17.46	21.22	22.48	23.67	32.6	1.112	1.022	.10	.27	545.	689.
20.	21.67	24.64	25.89	27.08	36.4	2.710	1.056	.10	.24	486.	588.
21.	17.05	25.03	26.92	28.64	41.0	.148	1.003	.068	.22	423.	584.
22.	25.24	27.70	28.94	30.14	39.8	4.710	1.099	.10	.22	439.	515.
23.	21.55	28.10	29.97	31.70	44.4	.494	1.010	.068	.20	396.	521.
24.	26.67	31.98	33.84	35.58	48.7	1.312	1.027	.068	.18	364.	457.
25.	32.99	37.19	39.02	40.78	54.6	3.090	1.064	.068	.16	324.	388.
26.	25.60	36.82	39.54	42.03	59.9	.181	1.004	.047	.15	290.	397.
27.	36.94	40.59	42.41	44.18	58.4	4.640	1.097	.068	.15	299.	352.
28.	35.43	43.82	46.51	49.03	67.8	.900	1.018	.047	.13	261.	334.
29.	41.25	48.41	51.09	53.61	72.9	1.742	1.035	.047	.12	243.	301.
30.	48.18	54.18	56.84	59.38	79.4	3.200	1.066	.047	.11	222.	266.
31.	41.49	55.83	59.70	63.26	89.2	.353	1.007	.033	.10	197.	262.
32.	56.94	61.80	64.42	66.98	87.9	5.730	1.122	.047	.10	197.	229.
33.	50.76	62.64	66.48	70.06	96.8	.925	1.019	.033	.091	183.	234.
34.	61.73	71.38	75.18	78.79	106.6	2.130	1.044	.033	.082	166.	204.
35.	72.25	80.27	84.04	87.67	116.5	3.860	1.080	.033	.075	151.	179.

Table 2.

Highpass 50-ohm 7-Element Chebyshev Filters,

Design Parameters and Component Values

FLTR NO.	FREQUENCY AT AP, 1, 3, 6 & 30 DB (KILOHERTZ) F-AP	F-1DB	F-3DB	F-6DB	F-30DB	R.C. (%)	VSWR (MAX.)	C1,7 (UF)	C3,5 (UF)	L2,6 (UH)	L4 (UH)
1.	3.79	3.49	3.35	3.22	2.5	5.730	1.122	1.00	.47	1491.	1284.
2.	5.27	4.48	4.24	4.04	3.0	1.687	1.034	1.00	.39	1202.	970.
3.	5.26	4.90	4.71	4.53	3.5	6.874	1.148	.68	.33	1063.	924.
4.	5.67	5.10	4.87	4.67	3.5	3.860	1.080	.75	.33	1026.	865.
5.	6.06	5.24	4.98	4.75	3.5	2.130	1.044	.82	.33	1017.	830.
6.	7.40	5.50	5.14	4.85	3.4	.353	1.007	1.00	.33	1049.	786.
7.	6.46	6.00	5.77	5.55	4.3	6.629	1.142	.56	.27	867.	752.
8.	7.50	6.44	6.10	5.82	4.3	1.930	1.039	.68	.27	832.	676.
9.	8.61	7.29	6.90	6.57	4.8	1.593	1.032	.62	.24	740.	595.
10.	8.11	7.47	7.16	6.88	5.2	5.600	1.119	.47	.22	697.	599.
11.	9.28	7.92	7.51	7.16	5.3	1.782	1.036	.56	.22	678.	548.
12.	11.41	8.28	7.73	7.29	5.1	.278	1.006	.68	.22	704.	522.
13.	10.02	9.18	8.80	8.45	6.4	5.159	1.109	.39	.18	567.	486.
14.	11.58	9.74	9.22	8.77	6.4	1.466	1.030	.47	.18	556.	445.
15.	12.17	11.08	10.61	10.19	7.7	4.710	1.099	.33	.15	470.	401.
16.	13.86	11.68	11.06	10.52	7.7	1.514	1.031	.39	.15	463.	371.
17.	17.07	12.18	11.36	10.70	7.5	.233	1.005	.47	.15	482.	355.
18.	15.46	13.97	13.36	12.81	9.7	4.112	1.086	.27	.12	374.	316.
19.	18.23	14.80	13.95	13.24	9.6	.949	1.019	.33	.12	373.	292.
20.	18.25	16.63	15.92	15.28	11.6	4.710	1.099	.22	.10	314.	267.
21.	28.05	18.48	17.15	16.10	11.2	.108	1.002	.33	.10	328.	235.
22.	22.22	20.26	19.39	18.62	14.1	4.776	1.100	.18	.082	257.	219.
23.	26.05	21.53	20.33	19.32	14.1	1.174	1.024	.22	.082	254.	201.
24.	26.89	24.47	23.42	22.48	17.0	4.640	1.097	.15	.068	213.	181.
25.	39.73	27.06	25.16	23.65	16.5	.148	1.003	.22	.068	221.	160.
26.	38.09	31.51	29.76	28.28	20.6	1.190	1.024	.15	.056	173.	137.
27.	37.87	34.89	33.47	32.19	24.5	5.730	1.122	.10	.047	149.	128.
28.	43.55	37.11	35.17	33.51	24.6	1.742	1.035	.12	.047	145.	117.
29.	56.12	39.03	36.34	34.19	24.0	.181	1.004	.15	.047	152.	111.
30.	45.21	41.82	40.15	38.63	29.5	6.137	1.131	.082	.039	124.	107.
31.	52.66	44.76	42.40	40.39	29.7	1.687	1.034	.10	.039	120.	97.
32.	52.61	48.95	47.06	45.32	34.8	6.874	1.148	.068	.033	106.	92.
33.	56.67	51.00	48.72	46.70	35.1	3.860	1.080	.075	.033	103.	86.
34.	60.65	52.44	49.79	47.52	35.1	2.130	1.044	.082	.033	102.	83.
35.	74.00	55.00	51.43	48.54	34.4	.353	1.007	.10	.033	105.	79.

How To Use The Fitler Tables

After the upper 6-dB cuttoff frequency is determined for the lowpass filter to be used in a specific NB NT TEMPEST test application, a suitable design is selected from Table 1. Since the TEMPEST test specification allows a ±25% variation in the actual 6-dB cutoff frequency, one or more suitable filter designs probably will be available from Table 1. Select whichever design is most convenient to construct. If the required cutoff frequency is outside the tabulated frequency range, then a simple scaling procedure is used to obtain a design for the higher or lower frequencies. After a design has been selected, the filter elements are connected according to the schematic diagram in Figure 1A. A similar procedure is used in the selection of the highpass filter, and the schematic diagram of Figure 2A is applicable.

For cutoff frequencies outside the tabulated frequency ranges of Tables 1 and 2, the following scaling equations are used to find the new component values: $L' = L/F$, $C' = C/F$ where L' and C' are the new component values, L and C are the tabulated values, and F, the scaling factor, equals fc'/fc where fc' is the new cutoff frequency and fc is the tabulated cutoff frequency, both chosen so F is an integral power of ten. For example, lowpass design #1 is scaled upwards from a 6-dB cutoff frequency of 6.33 kHz to 63.3 kHz by dividing the L and C tabulated values by ten (scaling factor, F = 10), and by multiplying all tabulated frequencies by ten. If a scaling factor of 1000 is used, all tabulated frequencies become megahertz and all capacitor values become nano-farads. The inductor values are reduced by a factor of 1/1000. As long as the scaling factor is an integral power of ten, the resulting new capacitor values will always be standard values.

Filter Construction and Other Considerations

The major problems associated with the selection and design of suitable 50-ohm lowpass and highpass filters for TEMPEST testing are eliminated by using Tables 1 and 2. However, the problems associated with the selection and purchasing of components, and the filter construction and testing still remain. For example, the proper filter components should be obtained in the least expensive and most expeditious manner. The components should be assembled in a way that will assure satisfactory performance, and proper test procedures should be used to confirm that the completed filters perform as expected. Unfortunately, the detailed discussion of these important considerations is beyond the scope of this article. However, this information is now available in the 16-page Home Study Course No. 71 (Component Selection and Test Procedures for LC Filters, see reference #6) which is published by Measurements and Control, 2994 W. Liberty Avenue, Pittsburgh, PA 15216. Those planning to construct passive LC filters are advised to obtain a copy of this course, which is one of five courses of the M & C filter series. The complete M & C Filter Series (Courses 67-71) may be obtained from M & C for $12 prepaid.

Filter Construction Example

To demonstrate an application of Table 1, a 50-ohm lowpass filter was constructed in breadboard form for a 6-dB cutoff frequency of 13.5 kHz. The completed filter is shown in Figure 3, and its measured stopband attenuation response is shown in Figure 4. Figure 4 is a photograph of the CRT display of a Hewlett-Packard Digital Spectrum Analyzer, Model 8568A, and it shows the filter output response between 5 and 55 MHz. A constant amplitude input signal for these

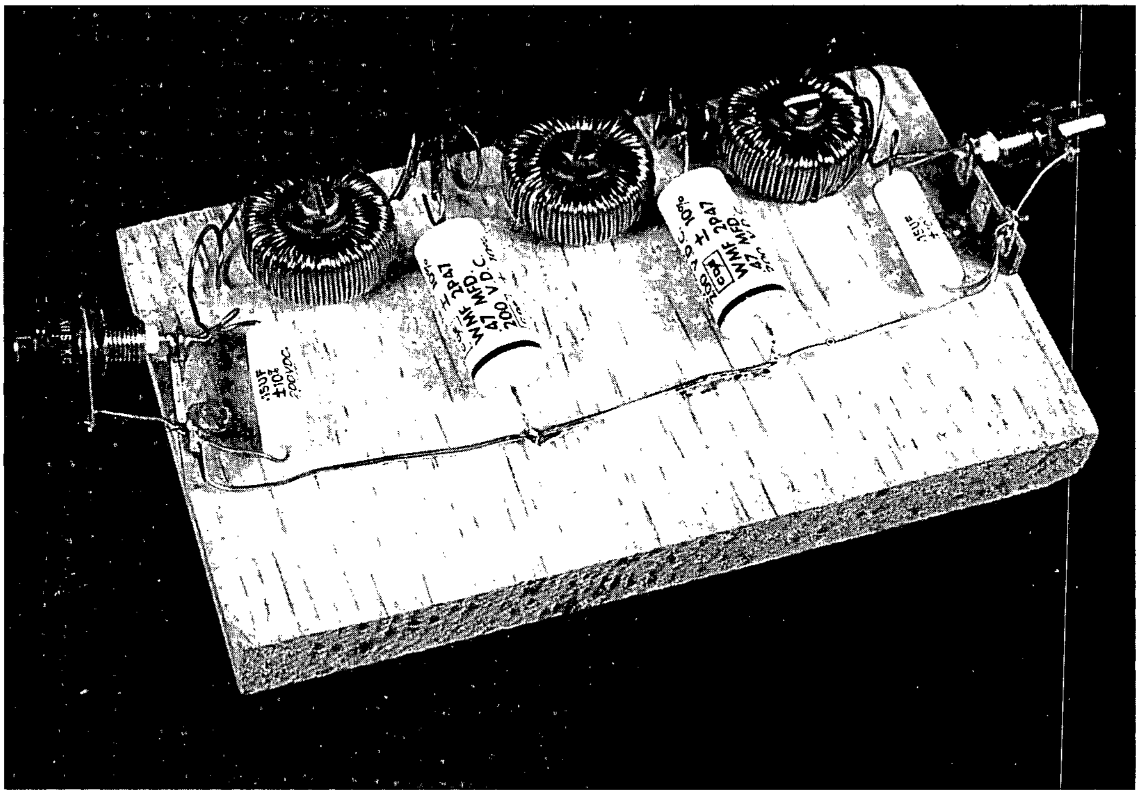


Figure 3. Assembled 13.5 kHz Lowpass Filter (Design #11, Table 1) Using Only Standard-Value Capacitors.

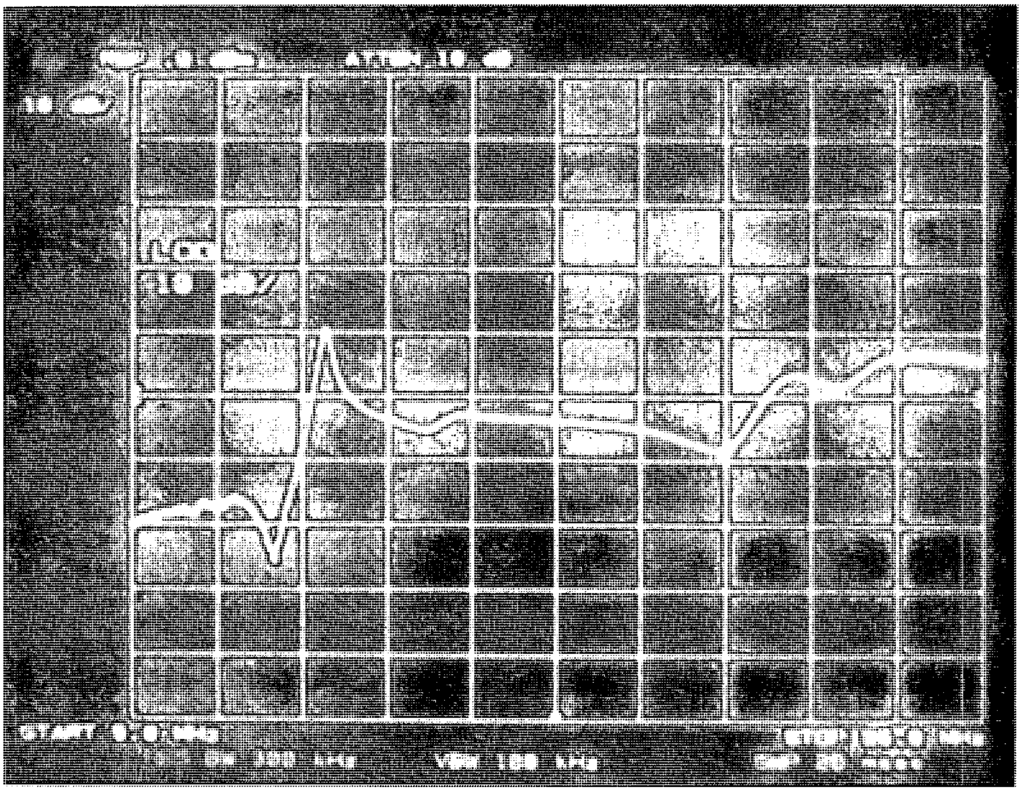


Figure 4. Measured Stopband Attenuation of the 13.5 kHz Lowpass Filter, 5 MHz to 55 MHz. Horizontal Scale: 5MHz/division; Vertical Scale: 10dB/division.

filter measurements was obtained from an H-P Model 8444A Tracking Generator. Each vertical division is 10 dB and each horizontal division is 5 MHz. The filter stopband attenuation exceeds 60 dB up to 15 MHz, above which the attenuation varies between 40 and 60 dB. The relative attenuation in the filter passband agrees within 1% with the 3, 6 and 30-dB frequencies listed in Table 1 for Design #1. The insertion loss of the filter at 5 kHz was about 0.2 dB. The capacitors used in the filter construction were standard .15 µF and .47 µF 200V Mylar capacitors selected to be within 1% of the design value. The inductors were hand-wound on molybdenum-permalloy cores obtained from 88 mH surplus telephone-line loading coils, (See reference #4). After the original windings were removed from the cores, 76 and 89 turns of #20 magnet wire were wound on the cores to make the 914 and 1241 µH inductors. These cores are excellent for winding high-Q inductors in the .2-mH to 3-mH inductance range for use over the 1-kHz to 20-kHz frequency range. Additional details regarding performance characteristics and sources for this component are discussed in the previously mentioned 16-page Home Study Filter Course No. 71.

Normalized Design Data for 7-Element Chebyshev Lowpass Filters

Table A-1 in Appendix A lists the normalized element values and other parameters of the Chebyshev filters listed in Tables 1 and 2. This data permits one to independently calculate the component values in Tables 1 and 2, and thereby makes it possible to confirm the correctness of the tabulated component values. Table A-2 lists normalized filter data for RC values between .2% and 7% in increments of 0.2%. This data, in combination with that of Table A-1 permits one to design new filters if the component values that happen to be on hand differ substantially (greater than ±5%) from the tabulated filter component values of Tables 1 and 2. The correctness of the normalized element values in Table A-2 can be easily verified by comparing the values with those published in A. Zverev's *Handbook of Filter Synthesis* (Reference #9). The normalized element values for the 7-element Chebyshev filters with reflection coefficients of 1 to 5% found in Zverev's reference are identical with those values in Table A-2. Since Table A-1 was developed from the same program that generated Table A-2, the data in Table A-1 is also correct.

An example will be given to demonstrate the use of the normalized filter data in Tables A-1 and Table A-2. Suppose a second lowpass filter having a 13.5 kHz 6-dB cutoff frequency is desired (see Table 1, Design #11); but, the only values of capacitor pairs available are at the opposite extremes of the nominal tolerance range of ±10%. That is, suppose C1 and C7 both are .165 µF (instead of .15 µF) and C3 and C5 are both .423 µF (instead of .47 µF). These capacitor values are sufficiently different from the tabulated standard values to require a separate new design calculation. (Note that if the filter capacitance requirements could have been satisfied with the Mallory polystyrene type SXM, which is available as a standard catalog item with a maximum tolerance of ±2.5%, then this type capacitor could have been used directly without any further concern.) When Mylar ®* capacitors are used, it is advisable to measure several capacitors having the nominal design value required, and select matched pairs closest to the design value. If the sellected values differ by more then ± 5% from the component values in Tables 1 and 2, then the procedure in the following design example should be used.

*DuPont Trademark

Examples of Lowpass and Highpass Filter Design Calculations

The first step in calculating a new Chebyshev lowpass filter design using capacitors of .165 μF and .423 μF is to determine the ratio of these two capacitors. Thus, C3/C1 = .423/.165 = 2.564. A Chebyshev design is now selected from one of the many normalized designs in Tables A-1 and A-2. The design which comes closest to matching the C-ratio of 2.564 should be used. A design with RC = 1.742 (from Table A-1) has a C-ratio of 2.553 which is within 0.5% of the desired ratio. This is close enough for our purposes. The listed normalized data and the F6/F-Ap ratio for this design will be used to calculate the component values and the 6-dB cutoff frequency of a new lowpass filter design. It will be interesting to see how the 6-dB cutoff frequency and the inductance values of the new lowpass filter will compare with those of the filter design #11 in Table 1. The following procedure is used:

The F-Ap and F-6 dB frequencies are calculated from equations 1(a) and 1(b):

1(a) F-Ap = G1/(C1·50·2π) and

1(b) F-6dB = F-Ap(F6/F-Ap ratio), where

RC = 1.742%, F6/F-Ap ratio = 1.300, G1,7 = .6091F, G2 = 1.262H, G3,5 = 1.555F, G4 = 1.561H, G3/G1 ratio = 2.553, C1 = .165 μF and C3 = .423 μF.

F-Ap = .6091/(.165·10^{-6}·50·2π) = 11.75 kHz

F-6dB = 11.75(1.300) kHz = 15.276 kHz

Note that the new 6-dB frequency is within +13% of the original value of 13.52 kHz. If this new 6-dB cutoff frequency is still within the ±25% window allowed by the TEMPEST test specification, then the design procedure may be continued. If not, a new design should be selected from Table 1 which will have a 6-dB cutoff frequency within the ±25% window allowed by the NB NT TEMPEST test specification.

L and C scaling factors are calculated:

2(a) ω = 2π·F-Ap = 2π(11.75)k = 73.827k

2(b) R/ω = 50/ω = 0.67726·10^{-3} (Inductance scaling factor)

2(c) 1/Rω = 1/(50·73.827k) = 0.2709·10^{-6} (Capacitance scaling factor)

Capacitor and inductor values are calculated. C1,7 should equal .165 μF and C3,5 should equal .423 μF (within .5%) otherwise there is an error in the calculations involving equations 2(a-c).

3(a) C1,7 = G1(1/Rω) = .6091(.2709) μF = 0.1650 μF

3(b) C3,5 = G3(1/Rω) = 1.555(.2709) μF = 0.42125μF (within 0.5% of expected value)

3(c) L2,6 = G2(R/ω) = 1.262(.67726)mH = 0.8547mH = 854.7 μH

3(d) L4 = G4(R/ω) = 1.561(.67726)mH = 1.0572mH = 1057 μH

This completes the calculations associated with the new lowpass filter design. The inductance values of L2 and L4 are both smaller than the original values of 914 and 1241 μH by 6.5% and 14.8%, respectively. This difference is large enough to warrant correction.

A similar procedure is used to design highpass filters except the equations of 1(a & b) and 3(a - d) are slightly modified. For the highpass filter design:

1(a) F-Ap = 1/(G1·C1·50·2π) and 1(b) F-6dB = F-Ap/(F6/F-Ap ratio)

3(a) C1,7 = 1/(G1·Rω)

3(b) C3,5 = 1/(G3·Rω)

3(c) L2,6 = R/(ω·G2)

3(d) L4 = R/(ω·G4)

For example, if C1 = 1.0 μF and C3 = .47 μF, the C1/C3 ration is 2.128, and the normalized data for RC = 5.730 in Table A-1 can be used to calculate the parameters of a highpass filter. Using equations 1(a & b) and 3(a - d) for the highpass filter, the reader can independently calculate the tabulated F-Ap, F-6 dB and component values for the highpass filter design #1 of Table 2.

Computer Program for Tabulating the Normalized Element Values and Other Parameters

Occasionally, the TEMPEST engineer will require a 7-element filter having a more abrupt increase in the attenuation response than that which is provided by the filters in Tables 1 and 2. For example, a filter may be needed to substantially attenuate an EUT clock signal so low level signals immediately above or below the clock signal frequency can be examined without the detection system being overloaded. For this particular application, the filters in Tables 1 and 2 are not selective enough because of their low reflection coefficient and VSWR values. If substantially higher levels of VSWR would be acceptable, a considerable improvement can be obtained in increased attenuation near the cutoff frequency. For example, lowpass filter design #1 has 30 dB of attenuation at 8.9 kHz. If a VSWR of 1.667 would be acceptable, an additional 14 dB of attenuation could be obtained at 8.9 kHz for the same 3-dB cutoff frequency as before. Of course, the maximum passband ripple amplitude (Ap) would be greater (.28 dB), but his probably would not matter for this particular application. Even higher VSWR and Ap levels will give correspondingly greater increases in attenuation, but the filter performance becomes much more sensitive relative to component tolerance variations. Consequently, greater care should be exercised in selecting closer tolerance components.

This aspect of the Chebyshev filter performance was not explored in more detail because of limited time and space; however, with the BASIC computer program listed in Table B-1, Appendix B, it is possible for the TEMPEST engineer to develop his own normalized design tables for any level of VSWR and attenuation desired. Of course, a computer is necessary to get a complete print-out as shown in Table B-2, but this design aid is becoming increasingly accessible to the average engineer.

Conclusion

Reasons were given for using the 7-element Chebyshev filter type in performing narrowband non-tunable TEMPEST tests. Thirty 50-ohm lowpass filter designs in which only standard-value capacitors were required were tabulated for one frequency decade. Frequency versus attenuation at the 1, 3, 6 and 30-dB levels were included in addition to other filter data. A similar table was included for highpass filters. A simple scaling procedure was explained to make the tables universally applicable for any cutoff frequency. Calculation examples showed how alternate designs could be determined if the capacitor values on hand differed substantially from the standard values. Normalized design data was tabulated for values of reflection coefficient between .11 and 30% to permit independent designs to be calculated. A lowpass filter was designed and constructed, and its performance was documented. References for suitable construction procedures were given.

The design techniques discussed in this article should be useful to those responsible for performing narrowband non-tunable TEMPEST tests. Any comments, suggestions, or criticisms will be appreciated, and they should be addressed to the author, Ed Wetherhold, Honeywell Inc., POB 391, Annapolis, MD 21404.

Acknowledgement

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APPENDIX A

Table A-1.

Normalized Element Values and Other Data for Filter Designs Listed in Table 1.

R.C. (%)	F6/F-AP (RATIO)	G1,7 (F)	G2,6 (H)	G3,5 (F)	G4 (H)	G3/G1 RATIO
.1078	1.743	.3438	.866	1.135	1.210	3.300
.1478	1.680	.3642	.906	1.178	1.252	3.235
.1806	1.642	.3780	.932	1.206	1.278	3.191
.2328	1.596	.3966	.967	1.243	1.312	3.133
.2777	1.565	.4103	.991	1.268	1.336	3.091
.3533	1.524	.4302	1.025	1.304	1.368	3.030
.3969	1.506	.4403	1.042	1.321	1.383	3.000
.4936	1.471	.4603	1.073	1.354	1.412	2.941
.6428	1.432	.4864	1.113	1.394	1.446	2.867
.7580	1.408	.5038	1.137	1.420	1.466	2.818
.9000	1.384	.5230	1.163	1.447	1.487	2.766
.9250	1.380	.5262	1.167	1.451	1.491	2.758
1.1120	1.356	.5485	1.195	1.481	1.513	2.700
1.3120	1.334	.5697	1.220	1.508	1.531	2.647
1.5140	1.317	.5890	1.241	1.532	1.547	2.600
1.7420	1.300	.6091	1.262	1.555	1.561	2.553
1.7820	1.297	.6125	1.265	1.559	1.563	2.545
2.1300	1.276	.6401	1.291	1.590	1.580	2.484
2.7100	1.250	.6807	1.324	1.634	1.601	2.400
3.0900	1.236	.7047	1.341	1.658	1.611	2.353
3.2000	1.232	.7114	1.346	1.665	1.613	2.341
3.4100	1.226	.7237	1.354	1.677	1.617	2.318
3.8600	1.213	.7489	1.369	1.702	1.624	2.273
4.6400	1.196	.7893	1.389	1.741	1.632	2.206
4.7100	1.194	.7927	1.391	1.744	1.633	2.200
5.6000	1.179	.8347	1.407	1.783	1.637	2.136
5.7300	1.176	.8406	1.409	1.789	1.637	2.128
6.8740	1.161	.8898	1.423	1.834	1.637	2.061

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APPENDIX A
Continued

Table A-2.

Normalized Element Values and Other Data for Lowpass Chebyshev Filters Having Reflection Coefficients Between 0.2 and 7%.

R.C. (%)	F6/F-AP (RATIO)	G1,7 (F)	G2,6 (H)	G3,5 (F)	G4 (H)	G3/G1 RATIO
.200	1.623	.3853	.946	1.221	1.292	3.168
.400	1.504	.4410	1.043	1.322	1.384	2.998
.600	1.442	.4793	1.102	1.384	1.437	2.886
.800	1.400	.5097	1.145	1.428	1.473	2.802
1.000	1.370	.5356	1.179	1.464	1.500	2.733
1.200	1.346	.5580	1.206	1.493	1.521	2.676
1.400	1.326	.5781	1.229	1.518	1.538	2.626
1.600	1.310	.5967	1.249	1.541	1.552	2.582
1.800	1.296	.6140	1.267	1.561	1.564	2.542
2.000	1.284	.6301	1.282	1.579	1.575	2.506
2.200	1.273	.6453	1.295	1.596	1.583	2.473
2.400	1.263	.6596	1.307	1.611	1.591	2.443
2.600	1.254	.6733	1.318	1.626	1.598	2.415
2.800	1.246	.6866	1.328	1.640	1.603	2.388
3.000	1.239	.6992	1.338	1.653	1.608	2.364
3.200	1.232	.7114	1.346	1.665	1.613	2.341
3.400	1.226	.7231	1.353	1.677	1.617	2.319
3.600	1.220	.7346	1.360	1.688	1.620	2.298
3.800	1.215	.7457	1.367	1.699	1.623	2.279
4.000	1.210	.7564	1.373	1.710	1.626	2.260
4.200	1.205	.7670	1.378	1.720	1.628	2.242
4.400	1.201	.7773	1.383	1.730	1.630	2.225
4.600	1.197	.7873	1.388	1.739	1.632	2.209
4.800	1.193	.7972	1.392	1.748	1.633	2.193
5.000	1.189	.8068	1.397	1.757	1.634	2.178
5.200	1.185	.8163	1.400	1.766	1.635	2.164
5.400	1.182	.8256	1.404	1.775	1.636	2.150
5.600	1.179	.8347	1.407	1.783	1.637	2.136
5.800	1.175	.8437	1.410	1.792	1.637	2.123
6.000	1.172	.8526	1.413	1.800	1.637	2.111
6.200	1.170	.8613	1.415	1.808	1.638	2.099
6.400	1.167	.8699	1.418	1.816	1.637	2.087
6.600	1.164	.8784	1.420	1.823	1.637	2.076
6.800	1.162	.8868	1.422	1.831	1.637	2.065
7.000	1.159	.8950	1.424	1.838	1.637	2.054

APPENDIX B

Table B-1.

BASIC Program for Calculation of Normalized Element Values and Other Parameters for 7-Element Chebyshev Lowpass Filters

```
 10 ♦THIS BASIC PROGRAM TABULATES THE NORMALIZED PARAMETERS OF 7-ELEMENT
 20 ♦CHEBYSHEV C-IN/OUT LOWPASS FILTERS, FCO=1 RAD/SEC (.159155 HZ) AND
 30 ♦R IN=R OUT=1 OHM. INDEPENDENT VARIABLE IS REFLECTION COEFFICIENT IN %
 40 DATA 1.41421,2.0,31.623  'ATTEN FACTORS FOR AS=3.01,6.02,& 30 DB'
 50 DIM A(3)
 60 FOR J = 1,3
 70 READ A(J)
 80 NEXT J
 90 DATA .2, 5.6, 6, 8, 10, 12, 15, 15.0874, 20, 25, 30   'R.C. IN % '
100 PRINT
110 PRINT "   R.C. VSWR  A-P F3/FAP F6/FAP F30/FAP";
120 PRINT "  G1,7  G2,6   G3,5    G4    G3/G1"
130 PRINT "   (%)  ---- (DB)  RATIO  RATIO  RATIO";
140 PRINT "   (F)   (H)     (F)     (H)   RATIO"
150 READ R      'REFLECTION COEFFICIENT IN %'
160 V = (1 + R/100)/(1 - R/100)          'CALCULATION OF VSWR'
170 A0 = -4.3429♦LOG(1-(R/100)^2)        'CALCULATION OF A-P(DB) VALUE'
180 E = SQR((.01♦R)^2/(1-(.01♦R)^2))   'CALCULATION OF RIPPLE FACTOR, E'
185 IF R < 1.0 GO TO 208
190 B = A0/17.37178                        'X = LN(COTH A/17.37178)'
200 X = LOG((EXP(B) + EXP(-B))/(EXP(B) - EXP(-B)))
204 GO TO 210
208 X = 2♦LOG(200/R)       'SPECIAL CALCULATION FOR R.C.<1.0% '
210 Y = .5♦(EXP(X/14) - EXP(-X/14))
220 G1 = .44505/Y             'G1,2,3 & 4 = NORMALIZED FILTER ELEMENT VALUES'
230 G2 = .554956/((Y^2 + .188255)♦G1)
240 G3 = 2.24698/((Y^2 + .611261)♦G2)
250 G4 = 3.603876/((Y^2 + .95048)♦G3)
260 FOR J = 1,3
270 T = ((A(J)^2-1)^.5)/E       'TN(W) = SQR(A^2-1)/E'
280 M1 = (1/7)♦LOG(T+SQR(T^2-1))    '1/N COSH-1 TN(W)'
290 W(J) = .5♦(EXP(M1) + EXP(-M1))    'CALC W FOR AS=3.01,6.02 & 30 DB'
300 NEXT J
310 PRINT,320, R, V, A0, W(1), W(2), W(3), G1, G2, G3, G4, G3/G1
320 FMT F7.3,F6.3,F5.3,F7.3,F7.3,F7.3,F7.3,F7.3,F7.3,F7.3,F8.4
330 GO TO 150
```

Table B-2.

Print-out of BASIC Program

R.C. (%)	VSWR ----	A-P (DB)	F3/FAP RATIO	F6/FAP RATIO	F30/FHP RATIO	G1,7 (F)	G2,6 (H)	G3,5 (F)	G4 (H)	G3/G1 RATIO
.200	1.004	.000	1.528	1.623	2.311	.385	.946	1.221	1.292	3.1685
5.600	1.119	.014	1.133	1.179	1.548	.835	1.407	1.783	1.637	2.1364
6.000	1.128	.016	1.128	1.172	1.536	.853	1.413	1.800	1.637	2.1109
8.000	1.174	.028	1.107	1.148	1.489	.935	1.431	1.874	1.633	2.0046
10.000	1.222	.044	1.093	1.131	1.455	1.010	1.437	1.941	1.622	1.9227
12.000	1.273	.063	1.081	1.117	1.427	1.080	1.435	2.004	1.605	1.8566
15.000	1.353	.099	1.068	1.101	1.395	1.178	1.423	2.094	1.574	1.7771
15.087	1.355	.100	1.068	1.101	1.394	1.181	1.423	2.097	1.573	1.7751
20.000	1.500	.177	1.053	1.083	1.355	1.335	1.388	2.240	1.515	1.6781
25.000	1.667	.280	1.042	1.069	1.325	1.488	1.343	2.388	1.451	1.6046
30.000	1.857	.410	1.034	1.059	1.301	1.643	1.291	2.542	1.385	1.5473

DATA
EXIT

LOSSYLINE FLEXIBLE FILTER WIRE AND CABLE

INTRODUCTION

LOSSYLINE cable is a single conductor flexible wire which possesses the properties of a magnetically and electrically shielded low-pass line filter in its ability to remove electromagnetic interference. The *LOSSYLINE* wire or cable solves a number of problems in interference filtering. These include leakage and coupling through shielding, avoidance of standing waves in long lines, suppression of transient spikes and ringing, and effective EMI filtering and suppression above 10 MHz.

The evolution of the *LOSSYLINE* cable occurred in two stages. The first stage was the development of a short, rigid element possessing the desired characteristics of a low-pass, high-frequency dissipative/absorptive lossy electromagnetic unit. The second stage of evolution was to incorporate these filtering principles and characteristics into single conductor type wire and cable.

APPLICATIONS

Many existing devices which are subject to electromagnetic interference could be retrofitted with filters. However, the cost of such retrofitting is usually high, or else there is no available space for a conventional filter box. A less expensive, space-saving approach is to replace existing wiring with *LOSSYLINE* interference dissipative wire or cable. A cost reduction is effected because of the ease of installation of the cable.

Conventional wiring, though possessing state-of-the-art shielding, will pick up some radiated interference. For this reason, filters usually are placed in close proximity to the system components to be protected, and may be required at both ends. With filters, there still may be a problem of leakage or radiation of high frequencies from the conductor to other conductors. Shielding may prove unreliable or impractical. Replacement of the conductor with *LOSSYLINE* is a solution.

Leakage or pick-up by conductors may be prohibitive when they span considerable distances. It may not be practical or feasible to install sufficient filters along a great length. The use of *LOSSYLINE* cable may be the answer. It is flexible and also will provide magnetic dissipative isolation.

LOSSYLINE filters dissipate waveforms in proportion to their rise time. This provides the opportunity to remove individual spikes which might pass through a simple rejective filter and ring between reflective points. Shields may provide current paths through planes of contact between dissimilar metals or through minute perforations. The RF dissipative approach is a neater more direct solution.

Long conductors with and without filters possess inductive and capacitive reactance which requires matching for the passage of alternating current. Excessive standing wave voltages may appear along their length. Since it provides small reactance in the pass-band, and dissipation for higher frequencies, the RF dissipative approach provides a solution to the matching and standing wave problems.

With the greater use of frequencies above 10 MHz, the fall-off of attenuation with an increase of frequency cannot be disregarded. A purely dissipative filter, providing no leakage path as the wavelength becomes shorter is particularly helpful in the microwave region.