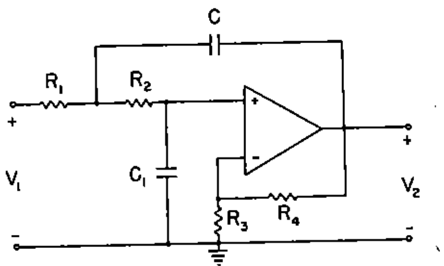
EECC560

Active Filter Design Charts

SUMMARY OF LOW-PASS SECOND-ORDER VCVS FILTER DESIGN PROCEDURE



General circuit.

Procedure

Given f_c (Hz), gain, and filter type (Butterworth or Chebyshev), perform the following steps:

1. Select a value of capacitance C, determining a K parameter from Fig. 2.12*a* if f_c is between 1 and $10^2 = 100$, from Fig. 2.12*b* if f_c is between 100 and $10^4 = 10{,}000$, and from Fig. 2.12*c* if f_c is between 10,000 and $10^6 = 1{,}000{,}000$ Hz.
2. Using this value of K, find the remaining element values of the circuit from the appropriate one of Figs. 2.13 through 2.17 for the Butterworth filter, and Figs. 2.18 through 2.32 for the Chebyshev filter, depending on the gain and, in the Chebyshev case, the dB ripple desired.
3. Select standard element values which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The curves are designed for 35 standard values of capacitance. Any intermediate values of capacitance may be used by observing that dividing the capacitance values by a constant k multiplies the cutoff frequency f_c by k. The resistances remain unchanged. This procedure of changing the capacitances may be accomplished by interpolation on the frequency versus K parameter graphs.

✓ If the op-amp to be used has a low-input resistance (less than 250 kΩ), values of K from 1 to 10 give best results. For higher input resistances (like 1 MΩ), K values up to 25 are acceptable, and for very high input resistances, such as those associated with field-effect transistor (FET) op-amps, values of K up to 100 may be used in most cases.

The values on the graphs for R_3 and R_4 were determined to minimize the dc offset of the op-amp. Other values of R_3 and R_4 may be used as long as the ratio R_4/R_3 is the same as that of the graph values. Standard element values of 5% tolerance normally yield acceptable results, but for best performance higher precision elements with values close to the graph values should be used. This is especially true for the higher gains where the element values are much more critical.

Finally there must be a dc return to ground at the filter input, the open-loop gain of the op-amp should be at least 50 times the gain of the filter at f_c, and the desired peak-to-peak voltage at f_c should not exceed $10^6/\pi f_c$ times the slew rate of the op-amp.

A specific example of a second-order design is given in Sec. 2.3.

$V_{p\text{-}p}$ at $f_c < \frac{10^6}{\pi f_c} \times$ slew rate of

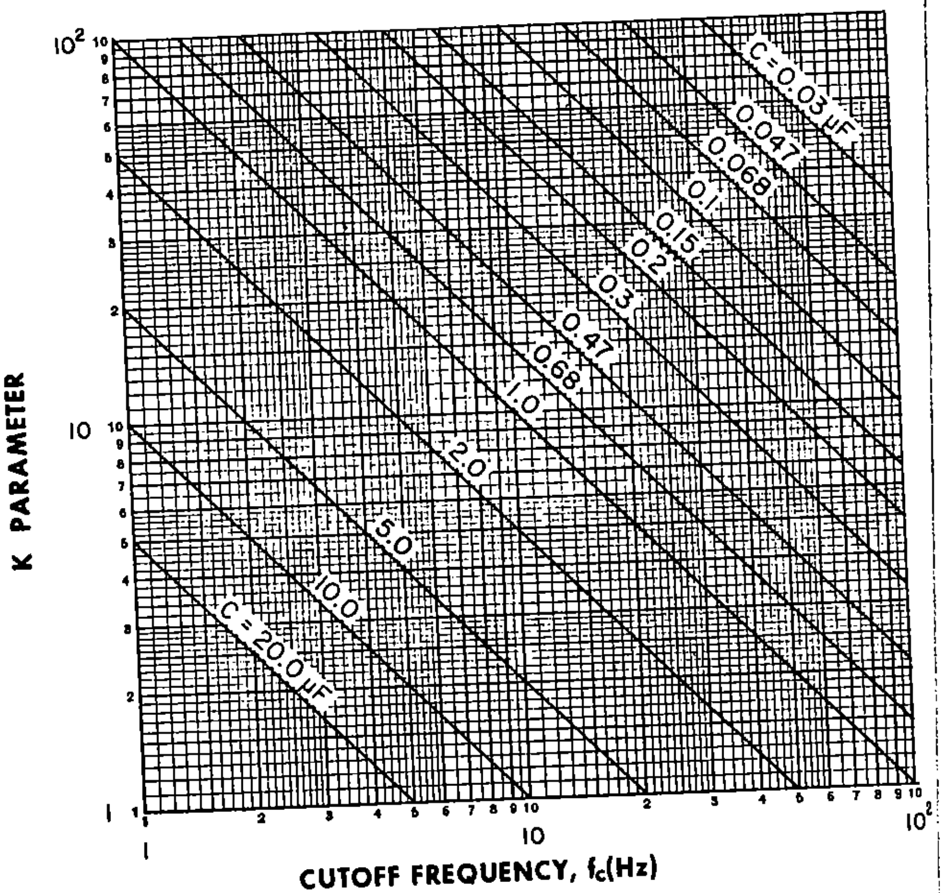


Fig. 2.12(*a*) *K* parameter versus frequency.

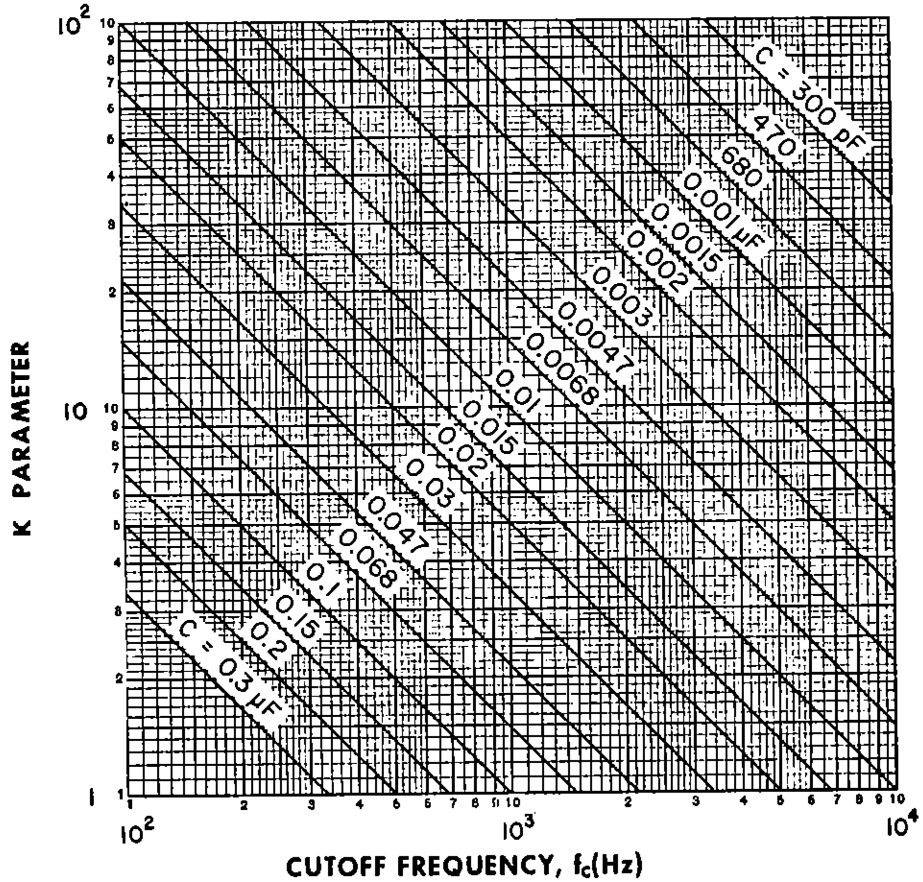


Fig. 2.12(*b*) *K* parameter versus frequency.

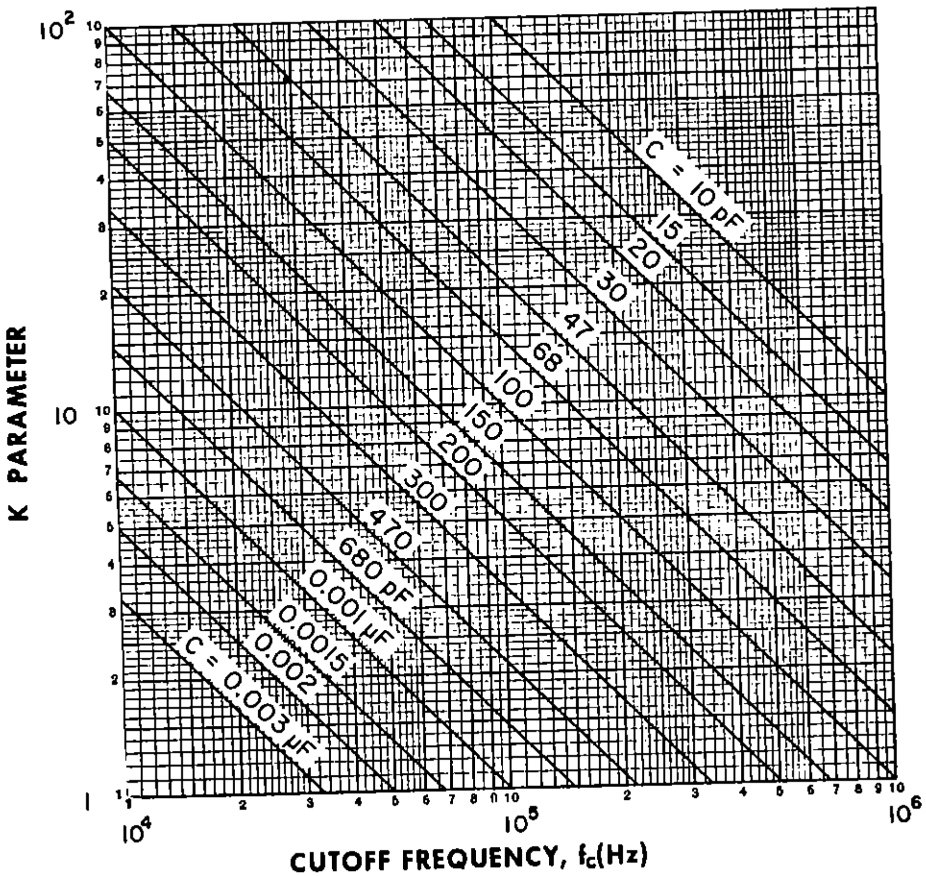


Fig. 2.12 (*c*) *K* parameter versus frequency.

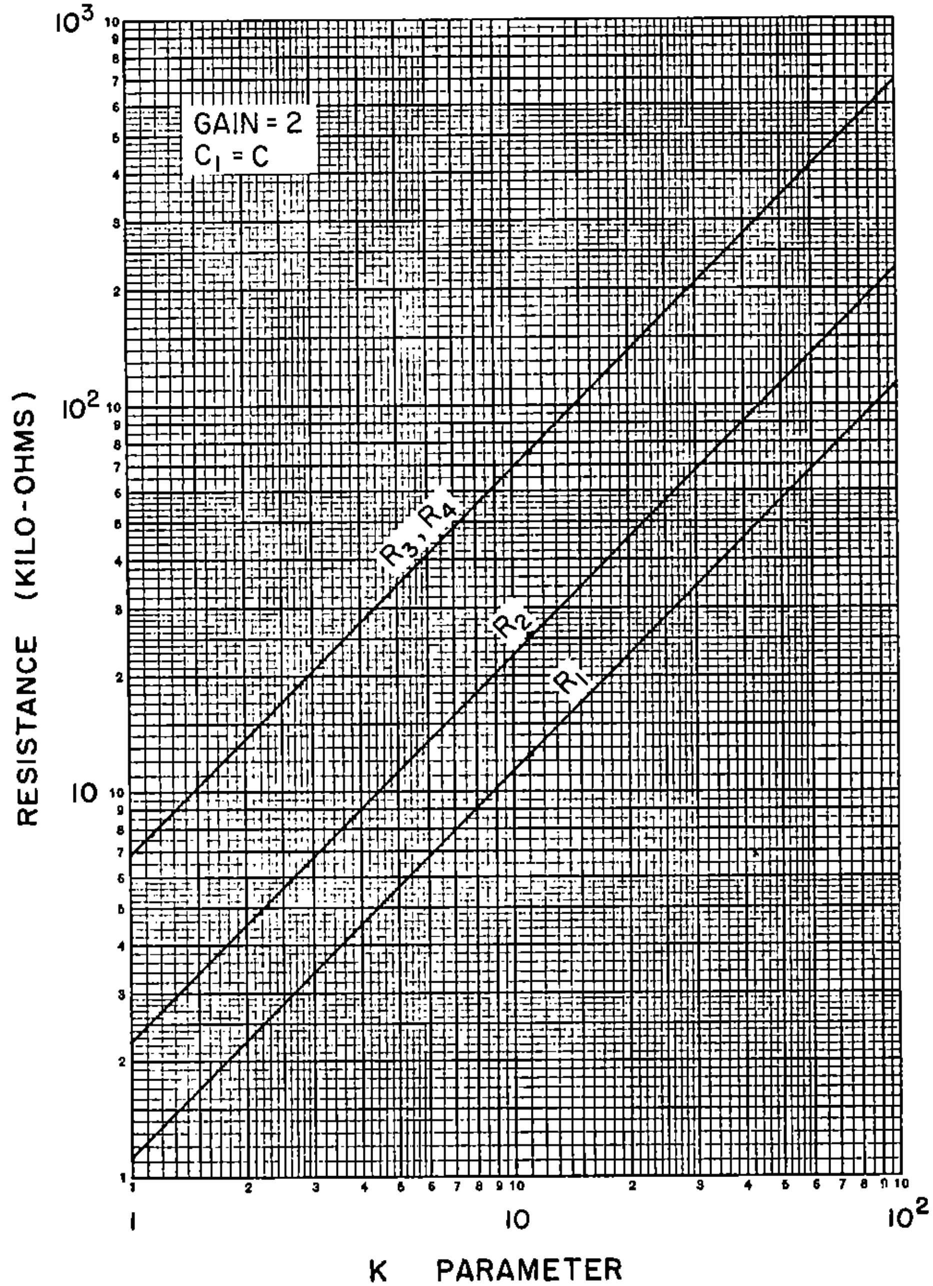


Fig. 2.13 Second-order VCVS low-pass Butterworth filter.

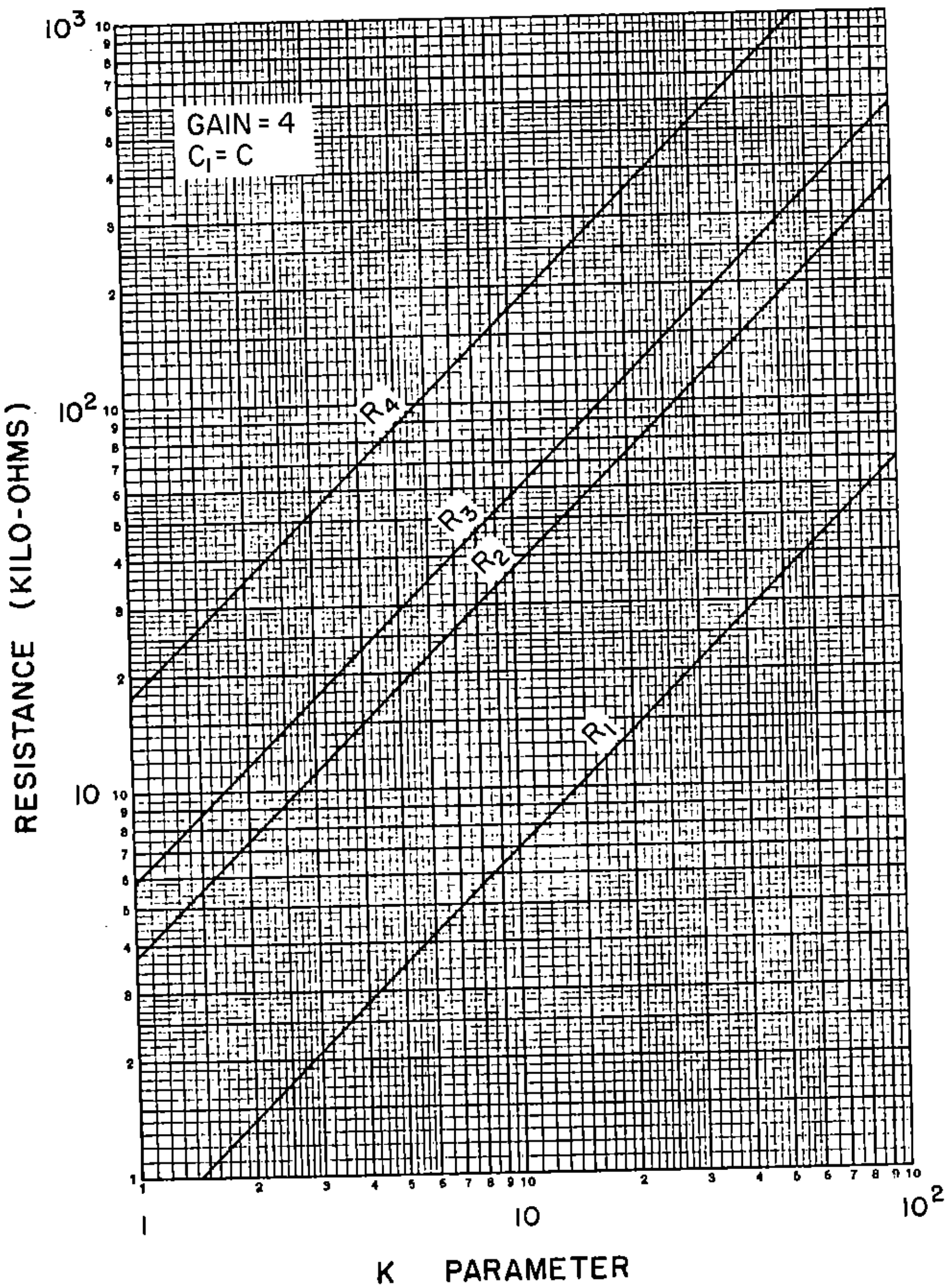


Fig. 2.14 Second-order VCVS low-pass Butterworth filter.

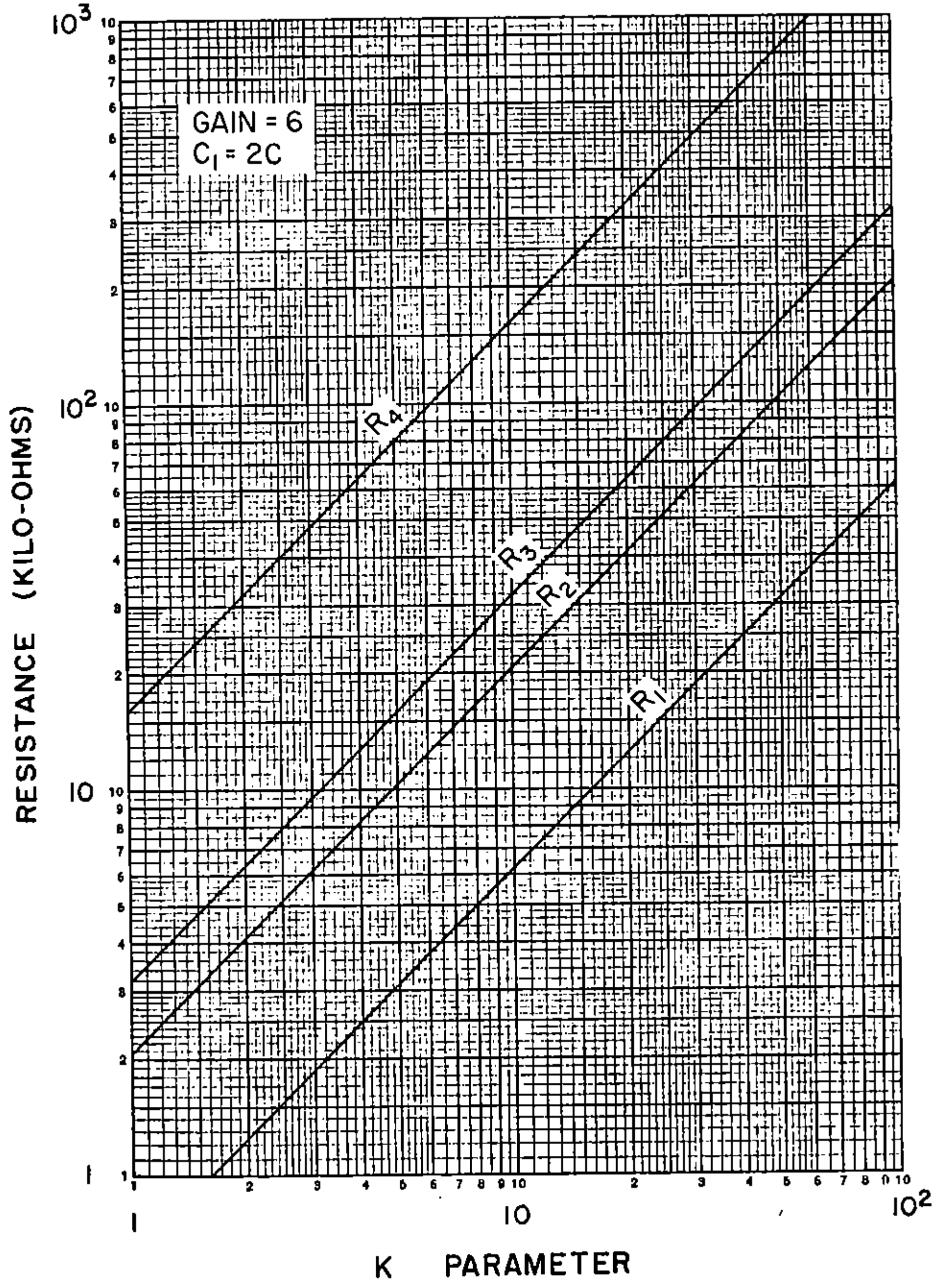


Fig. 2.15 Second-order VCVS low-pass Butterworth filter.

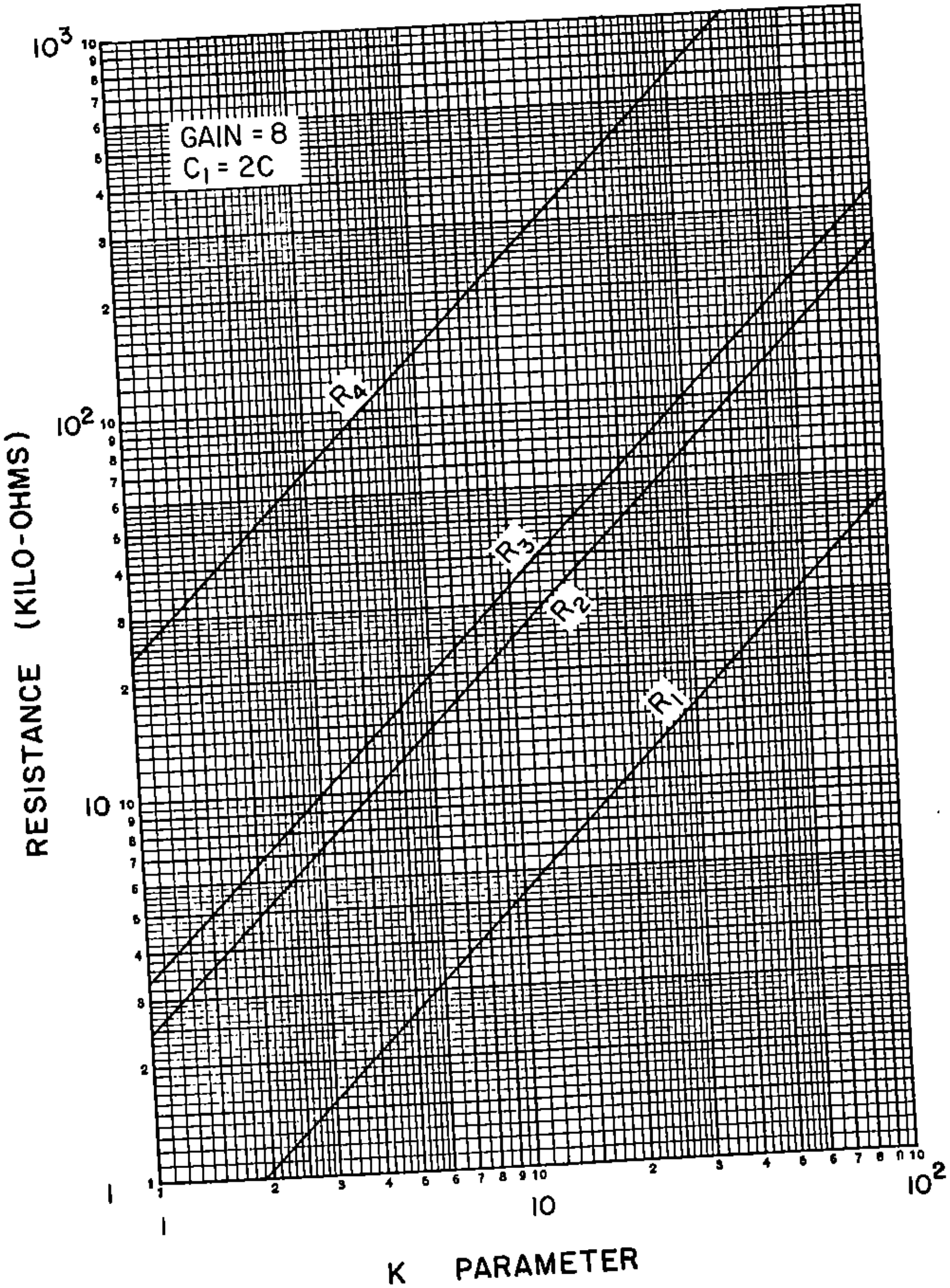


Fig. 2.16 Second-order VCVS low-pass Butterworth filter.

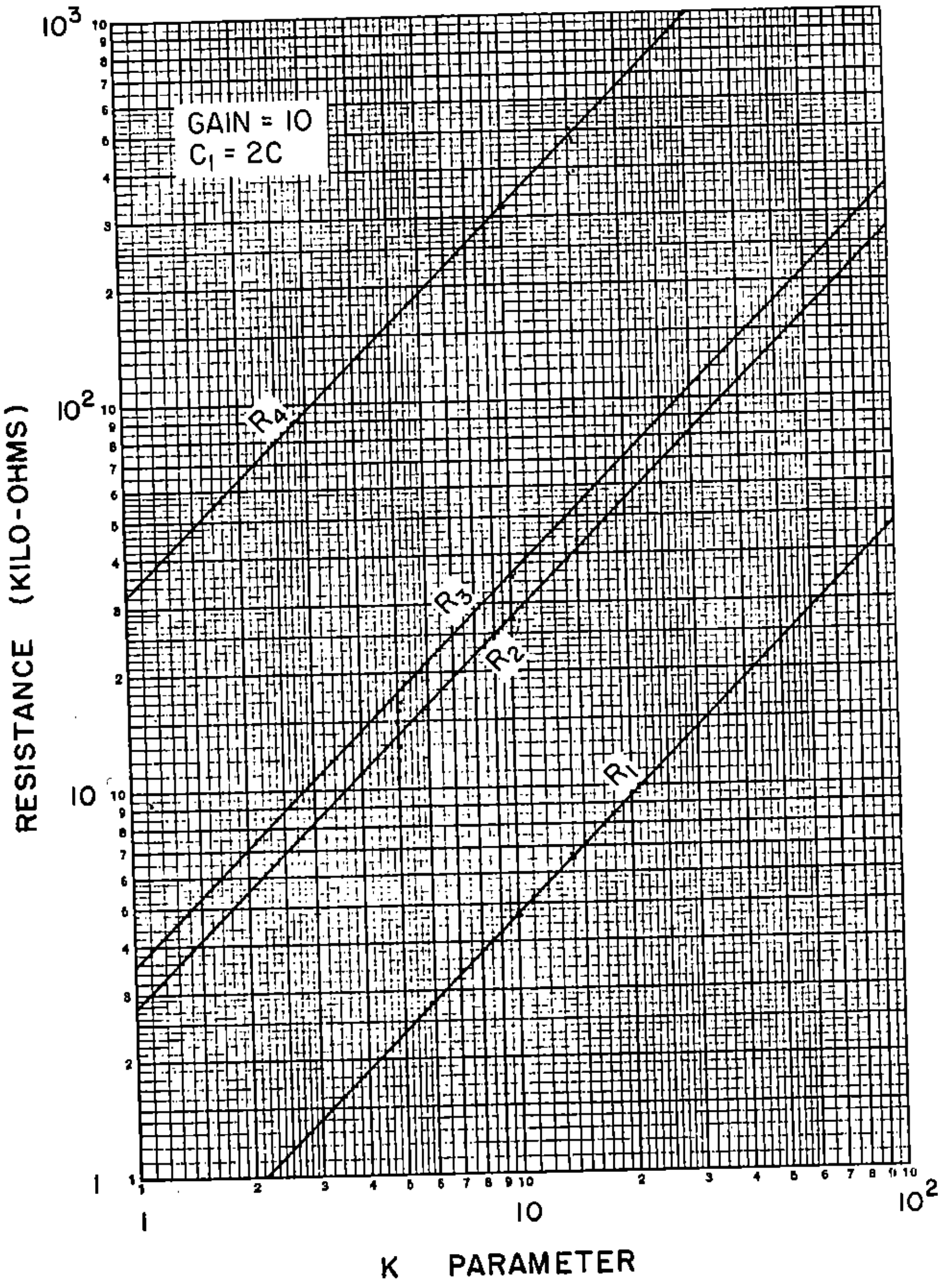


Fig. 2.17 Second-order VCVS low-pass Butterworth filter.

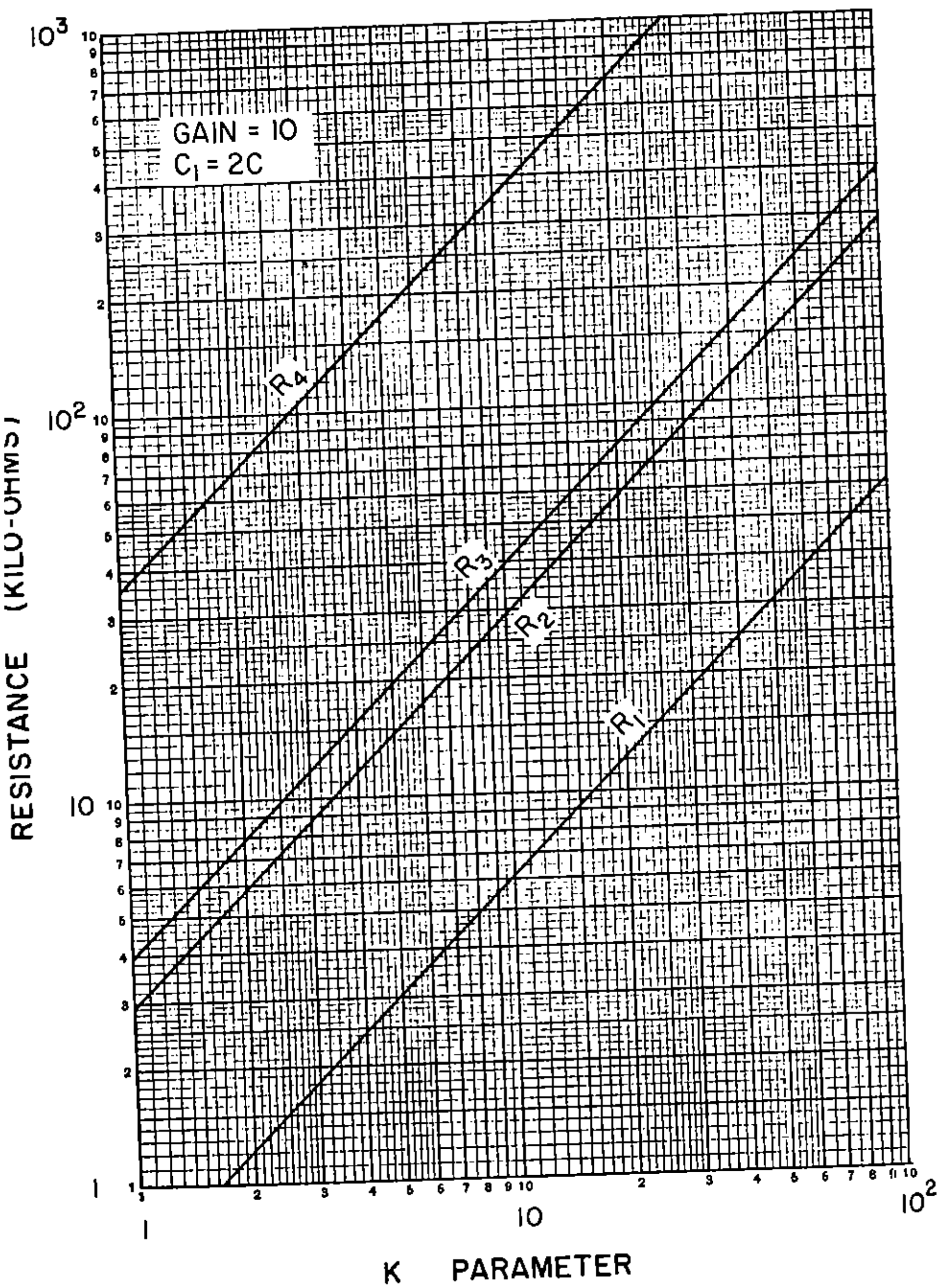
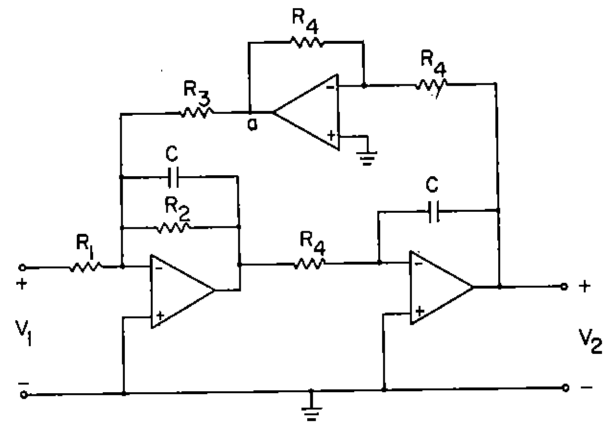


Fig. 2.32 Second-order VCVS low-pass Chebyshev filter (3 dB).

SUMMARY OF LOW-PASS SECOND-ORDER BIQUAD FILTER DESIGN PROCEDURE



General circuit.

Procedure

Given f_c (Hz), gain, and filter type (Butterworth or Chebyshev), perform the following steps:

1. Select a value of capacitance C, determining a K parameter from Fig. 2.12*a*, *b*, or *c*, as described in the second-order VCVS low-pass case.
2. Using this value of K and the given gain, find the resistance values of the circuit from the appropriate one of Fig. 2.33 for the Butterworth filter and Figs. 2.34 through 2.38 for the Chebyshev filter, depending, in the Chebyshev case, on the dB ripple desired.
3. Select standard resistance values which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The suggestions given in the second-order VCVS low-pass case apply except that there are three op-amps instead of one and there is no resistance ratio to be used in minimizing the dc offset of the op-amps. Also the dc return to ground requirement is satisfied by resistors R_2 and R_3. The gain is R_3/R_1 and an inverting gain (negative) of the same magnitude may be obtained by taking the output at node a. The filter response is readily adjusted by varying R_1, R_2, and R_3. Varying R_1 affects the gain, varying R_2 affects the passband response, and varying R_3 affects f_c.

The second-order biquad low-pass circuit is discussed in Sec. 2.1.

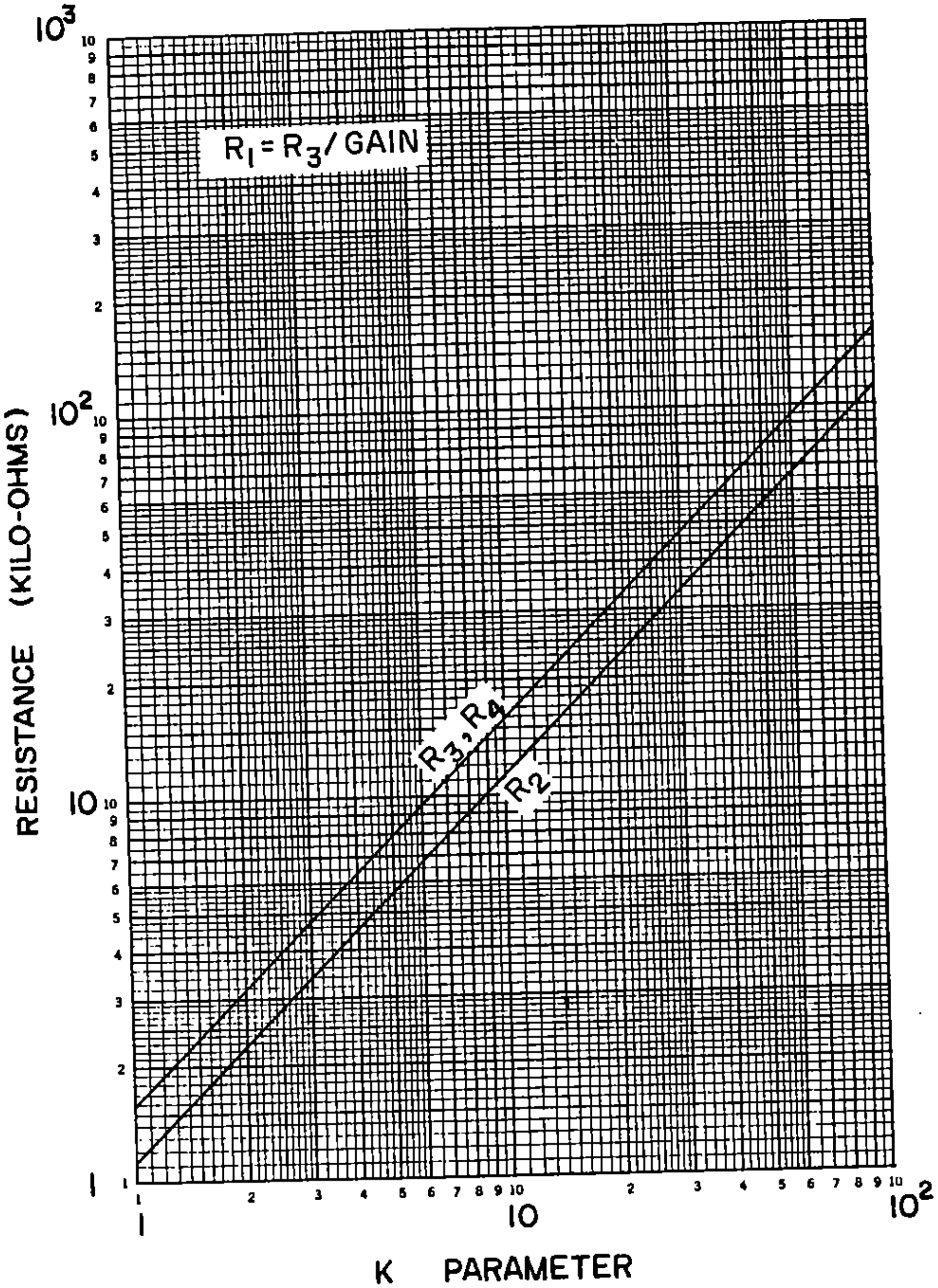


Fig. 2.33 Second-order biquad low-pass Butterworth filter.

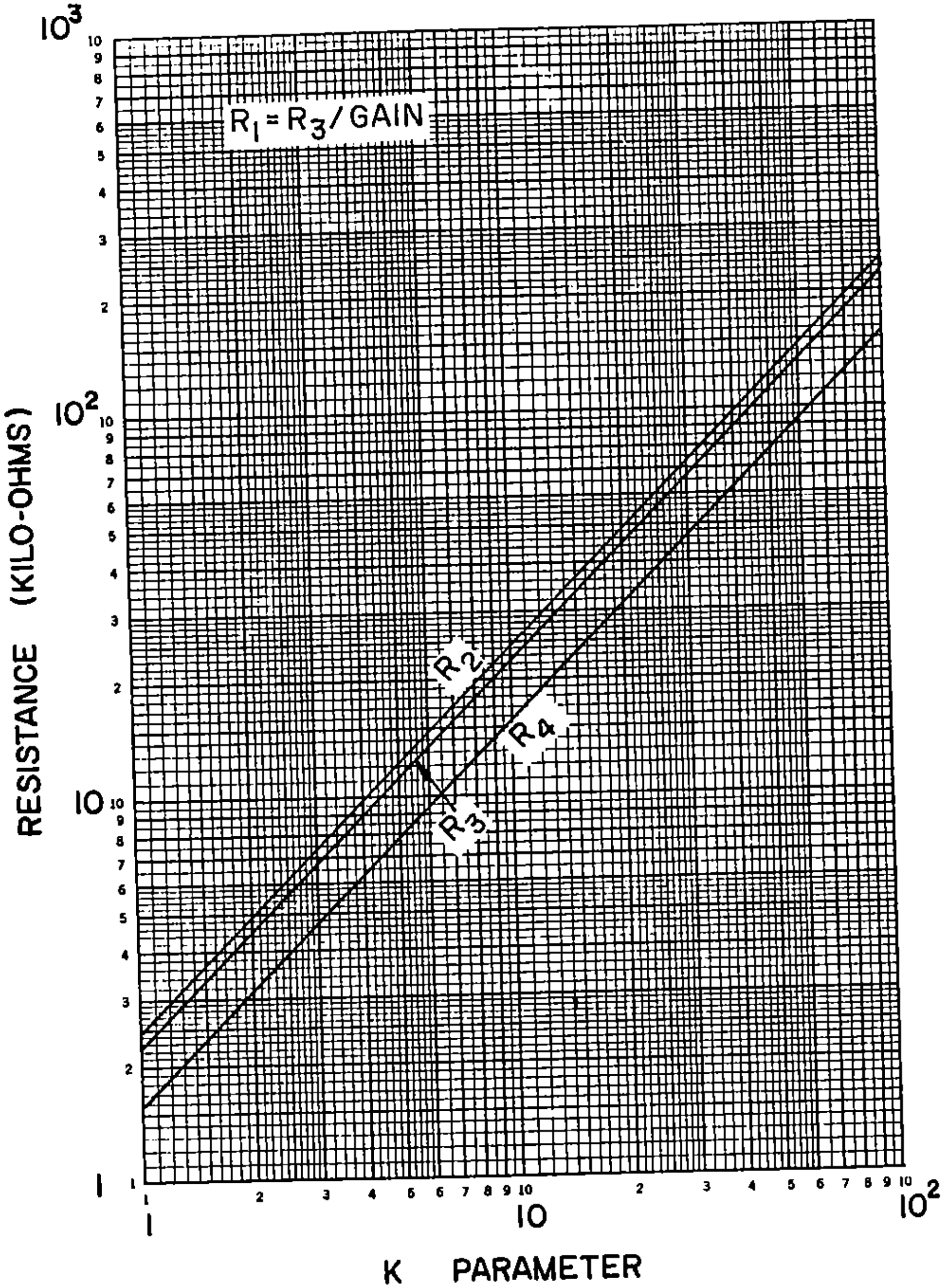
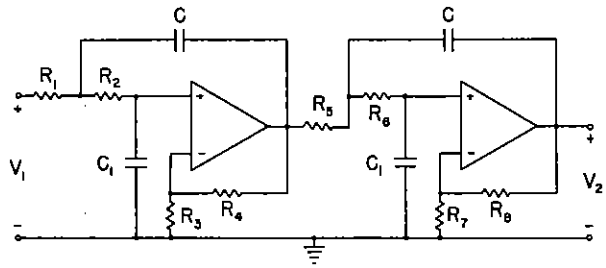


Fig. 2.38 Second-order biquad low-pass Chebyshev filter (3 dB).

SUMMARY OF LOW-PASS FOURTH-ORDER VCVS FILTER DESIGN PROCEDURE



General Circuit.

Procedure

Given f_c (Hz), gain, and filter type (Butterworth or Chebyshev), perform the following steps:

1. Select a value of capacitance C, determining a K parameter from Fig. 2.12*a*, *b*, or *c*, as described in the second-order VCVS low-pass case.
2. Using this value of K find the remaining element values of the circuit from the appropriate one of Figs. 2.39 through 2.41 for the Butterworth filter, and Figs. 2.42 through 2.56 for the Chebyshev filter, depending on the gain and, in the Chebyshev case, the dB ripple desired.
3. Select standard element values which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The suggestions given in the second-order VCVS low-pass case apply except that the open-loop gain of the op-amps should be at least 50 times the square root of the filter gain. The remarks in the second-order case for R_3 and R_4 apply also to R_7 and R_8.

A specific example is given in Sec. 2.6.

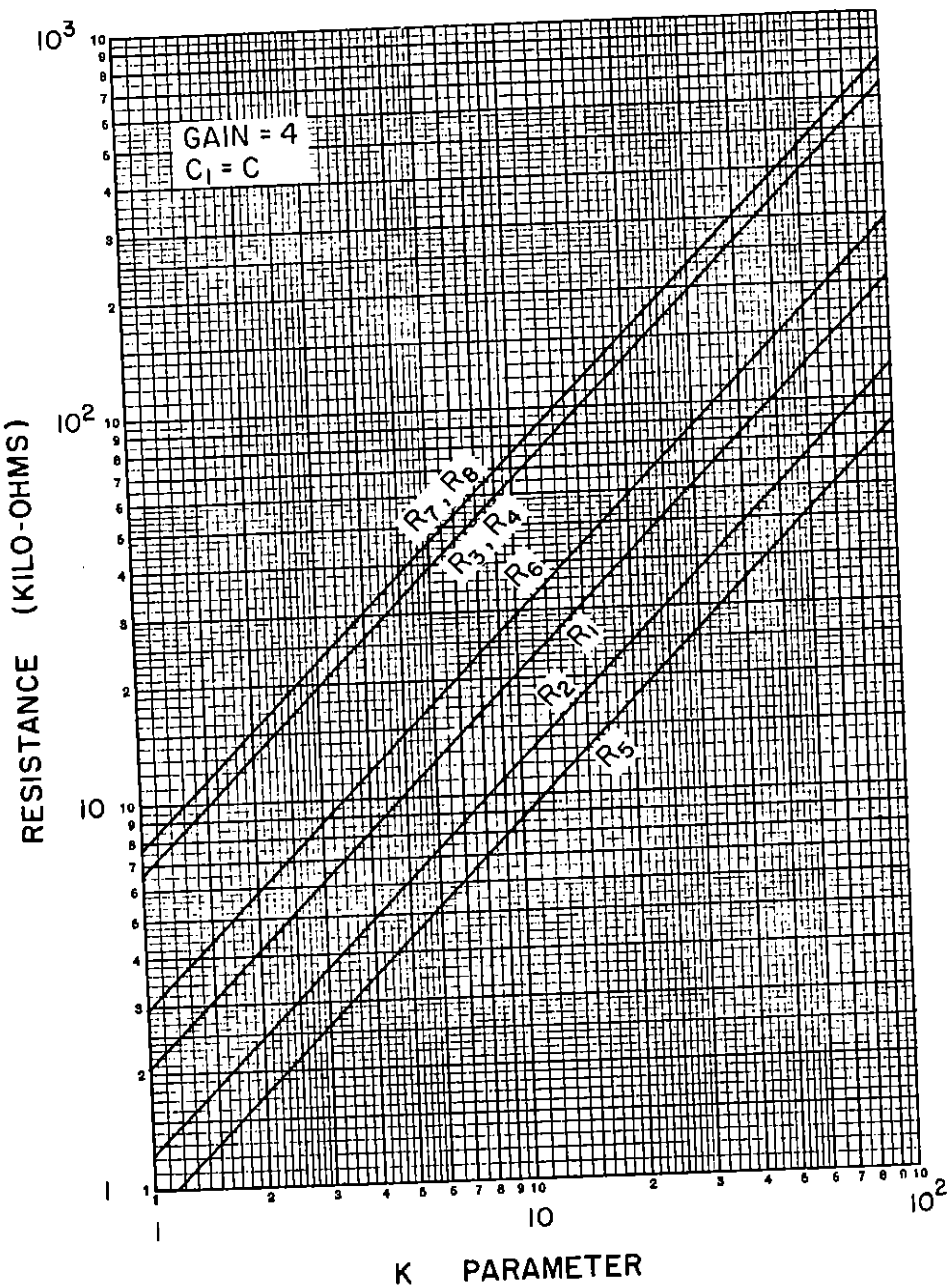


Fig. 2.39 Fourth-order VCVS low-pass Butterworth filter.

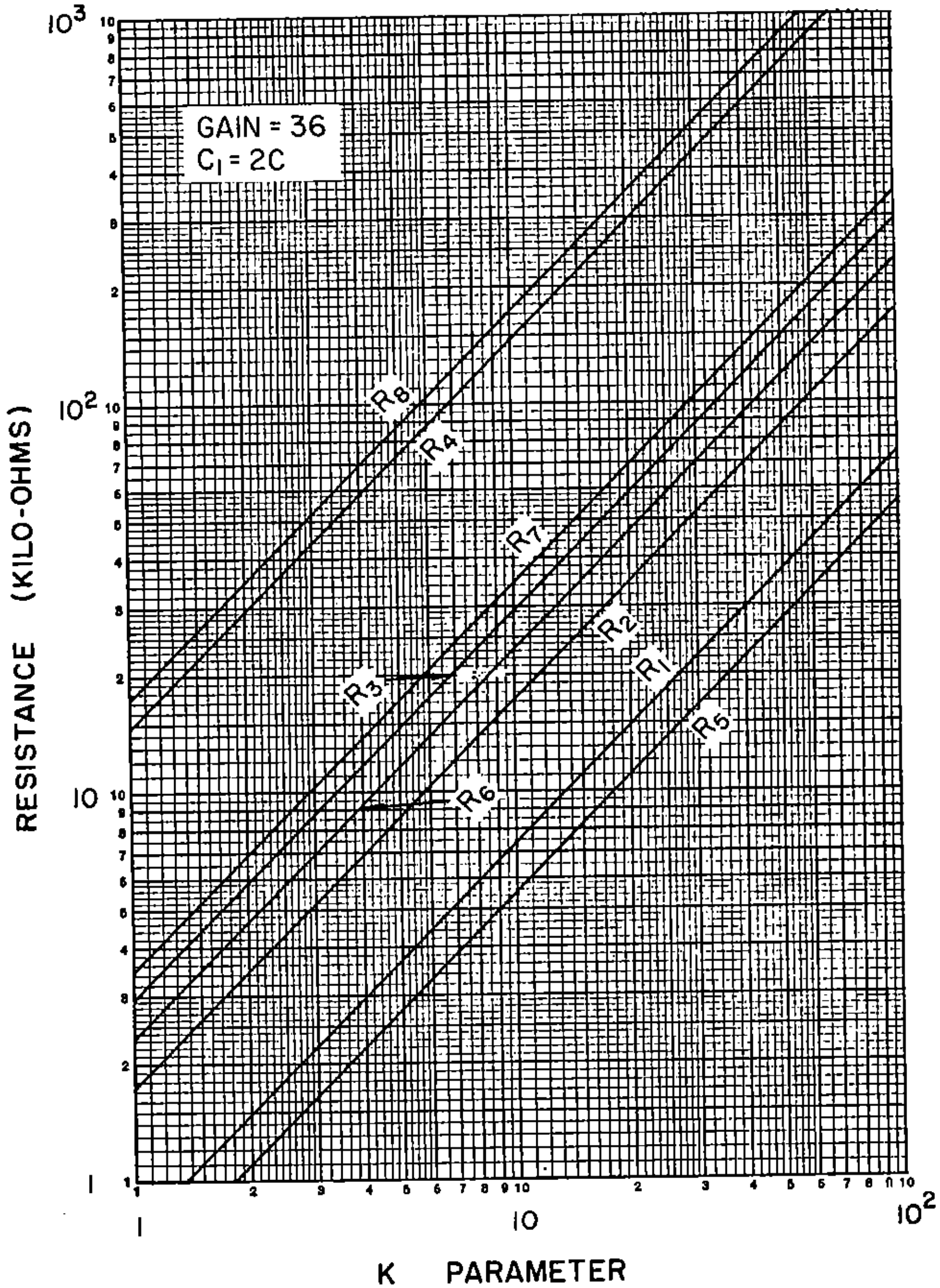


Fig. 2.40 Fourth-order VCVS low-pass Butterworth filter.

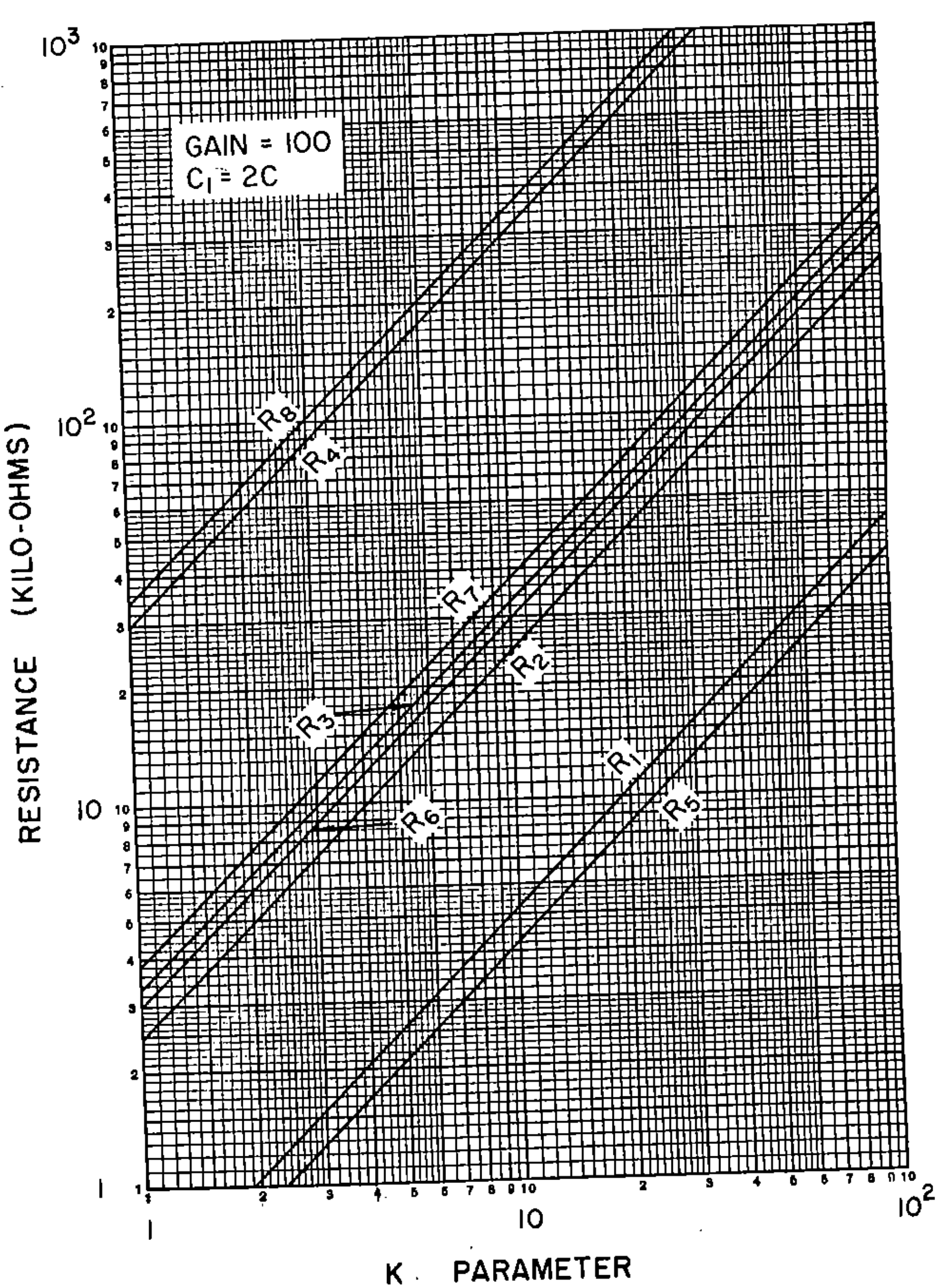


Fig. 2.41 Fourth-order VCVS low-pass Butterworth filter.

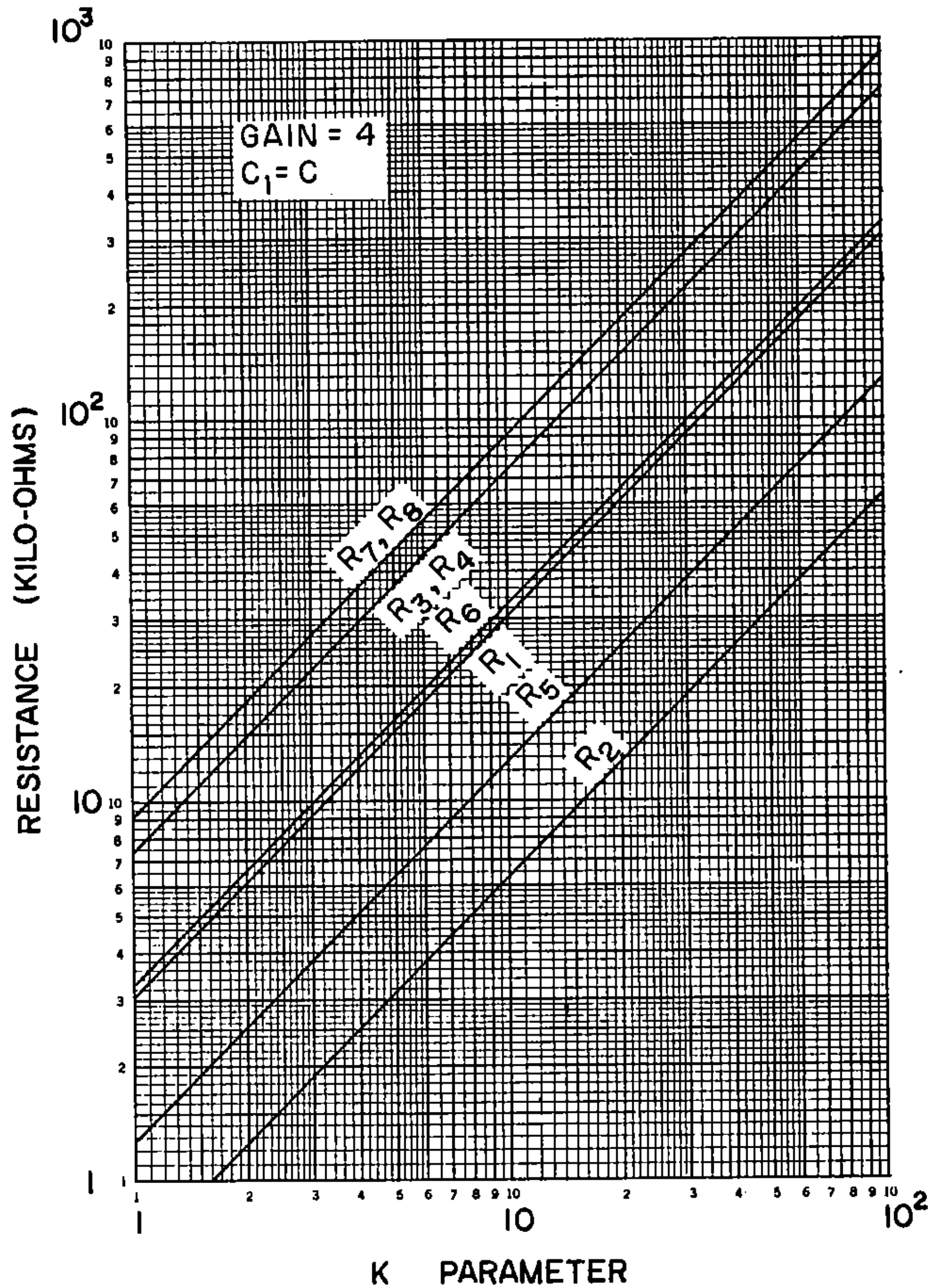
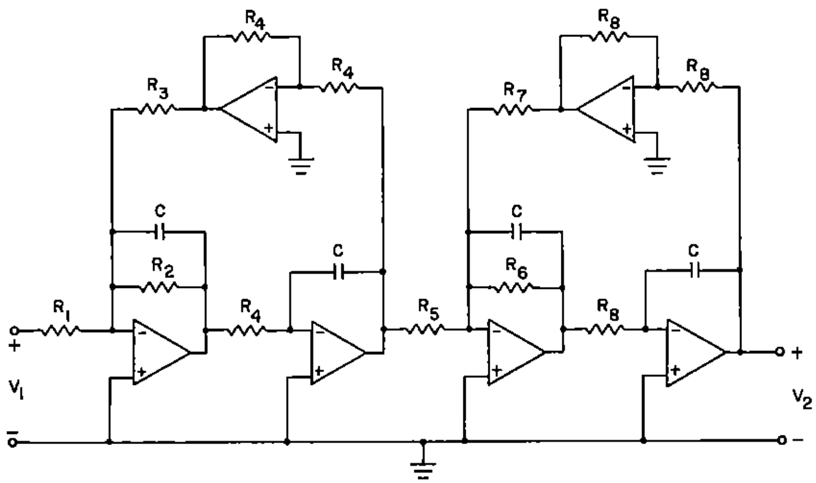


Fig. 2.42 Fourth-order VCVS low-pass Chebyshev filter (1/10 dB).

SUMMARY OF LOW-PASS FOURTH-ORDER BIQUAD FILTER DESIGN PROCEDURE



General circuit.

Procedure

Given f_c (Hz), gain, and filter type (Butterworth or Chebyshev), perform the following steps:

1. Select a value of C, determining a K parameter from Fig. 2.12*a*, *b*, or *c*, as described in the second-order VCVS low-pass case.
2. Using this value of K and the given gain, find the resistance values of the circuit from the appropriate one of Fig. 2.57 for the Butterworth filter and Figs. 2.58 through 2.62 for the Chebyshev filter, depending, in the Chebyshev case, on the dB ripple desired.
3. Select standard resistance values which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The suggestions given in the second-order VCVS low-pass case apply except that there are six op-amps instead of one and there is no resistance ratio to be used in minimizing the dc offset of

the op-amps. Also the dc return to ground requirement is satisfied by resistors R_2, R_3, R_6, and R_7.

The graphs are drawn for each stage to have the square root of the gain ($\sqrt{\text{GAIN}}$). The gain may be distributed differently by setting the gain of the first stage at G_1 ($R_1 = R_3/G_1$) and the gain of the second stage at G_2 ($R_5 = R_7/G_2$), so long as the product of G_1 and G_2 is the filter gain (GAIN).

The filter response may be adjusted by varying R_1 and R_5 to affect the gains, varying R_2 and R_6 to affect the passband response, and varying R_3 and R_7 to affect f_c.

The fourth-order biquad low-pass circuit is discussed in Sec. 2.6.

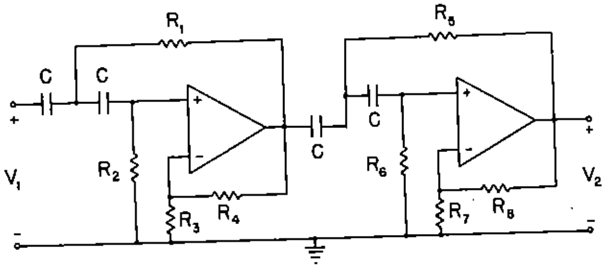


Fig. 3.4 A fourth-order high-pass filter.

3.3 Fourth-Order High-Pass Filters

To obtain either fourth-order Butterworth or Chebyshev high-pass filters, we use the circuit of Fig. 3.4, which is a cascading of two circuits of the type shown in Fig. 3.2. For a given f_c and C, we may obtain a practical circuit as described in detail in the summary at the end of the chapter.

As in the second-order case, for the Butterworth filter f_c is the cutoff point, but for the Chebyshev filter, f_c is the beginning of the ripple channel. For the fourth-order high-pass Chebyshev filter the cutoff point is 0.824 f_c

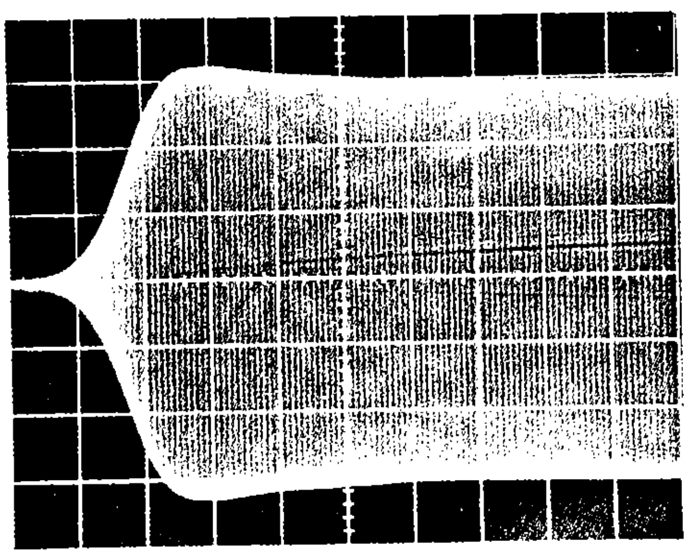


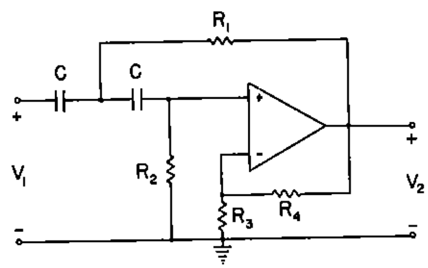
Fig. 3.5 A fourth-order high-pass Butterworth response.

for the $\frac{1}{10}$ dB case, 0.917 f_c for the $\frac{1}{2}$ dB case, 0.952 f_c for the 1 dB case, 0.980 f_c for the 2 dB case, and f_c for the 3 dB case.

As an example, we obtain a fourth-order Butterworth high-pass filter with f_c = 10,000 Hz, C = 200 pF, and a gain of 4. From Fig. 3.6*c*, we have the K parameter = 50, and from Fig. 3.28, we have R_1 = 73 kΩ, R_2 = 87 kΩ, $R_3 = R_4$ = 174 kΩ, R_5 = 104 kΩ, R_6 = 62 kΩ, and $R_7 = R_8$ = 123 kΩ. Using standard resistances of 72, 87, 180, 100, 62, and 120 kΩ, we obtain a filter with response shown in Fig. 3.5. Two μA709 op-amps were used in the two stages, both compensated as in the example of Sec. 3.2. The scale in the picture starts at 0 Hz and each division represents 5000 Hz. The actual results were f_c = 9595 Hz, with a gain of 4.5.

A summary of the techniques for constructing high-pass filters is given following this section. The second-order filters, together with their graphs, are presented first, followed by the fourth-order filters and their graphs.

SUMMARY OF HIGH-PASS SECOND-ORDER FILTER DESIGN PROCEDURE



General circuit.

Procedure

Given f_c (Hz), gain, and filter type (Butterworth or Chebyshev), perform the following steps:

1. **Select a value of capacitance C, determining a K parameter from Fig. 3.6*a* if f_c is between 1 and 10^2 = 100, from Fig. 3.6*b* if f_c is between 100 and 10^4 = 10,000, and from Fig. 3.6*c* if f_c is between 10,000 and 10^6 = 1,000,000 Hz.**
2. **Using this value of K, find the resistance values of the circuit from the appropriate one of Figs. 3.7 through 3.12 for the Butterworth filter, and Figs. 3.13 through 3.27 for the**

Chebyshev filter, depending on the gain and, in the Chebyshev case, the dB ripple desired.

3. Select standard resistance values which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

These are exactly like those of the low-pass second-order case, except that the dc return to ground is already satisfied by the resistor R_2.

A specific example is given in Sec. 3.2.

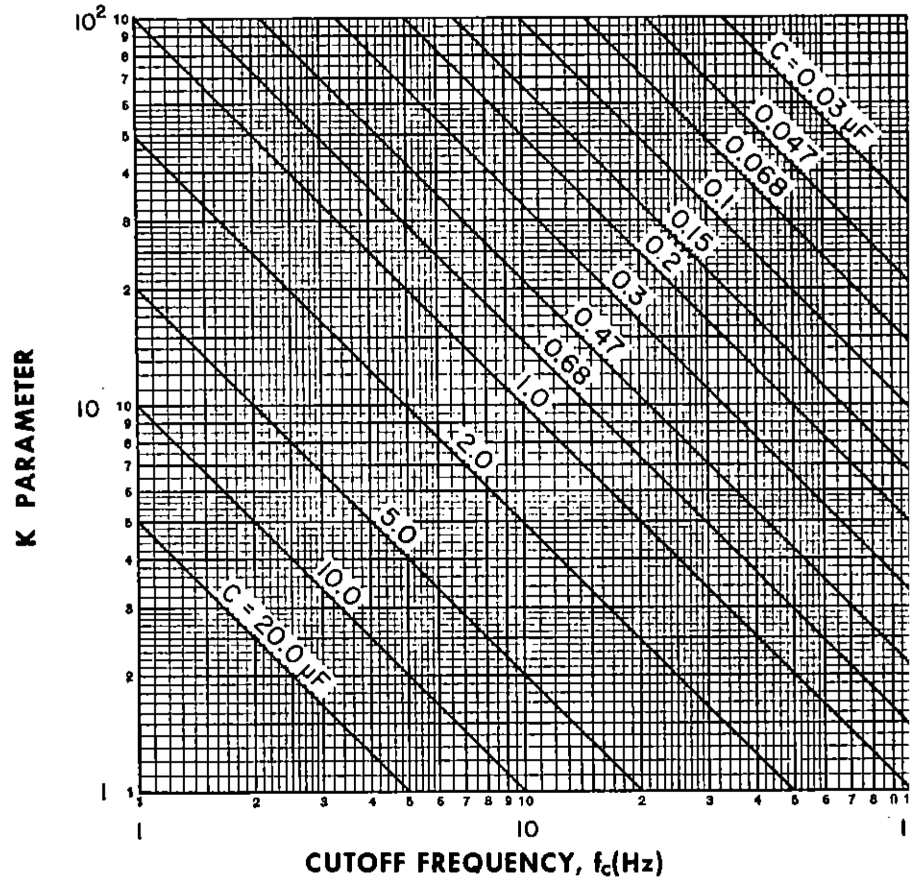


Fig. 3.6(*a*) *K* parameter versus frequency.

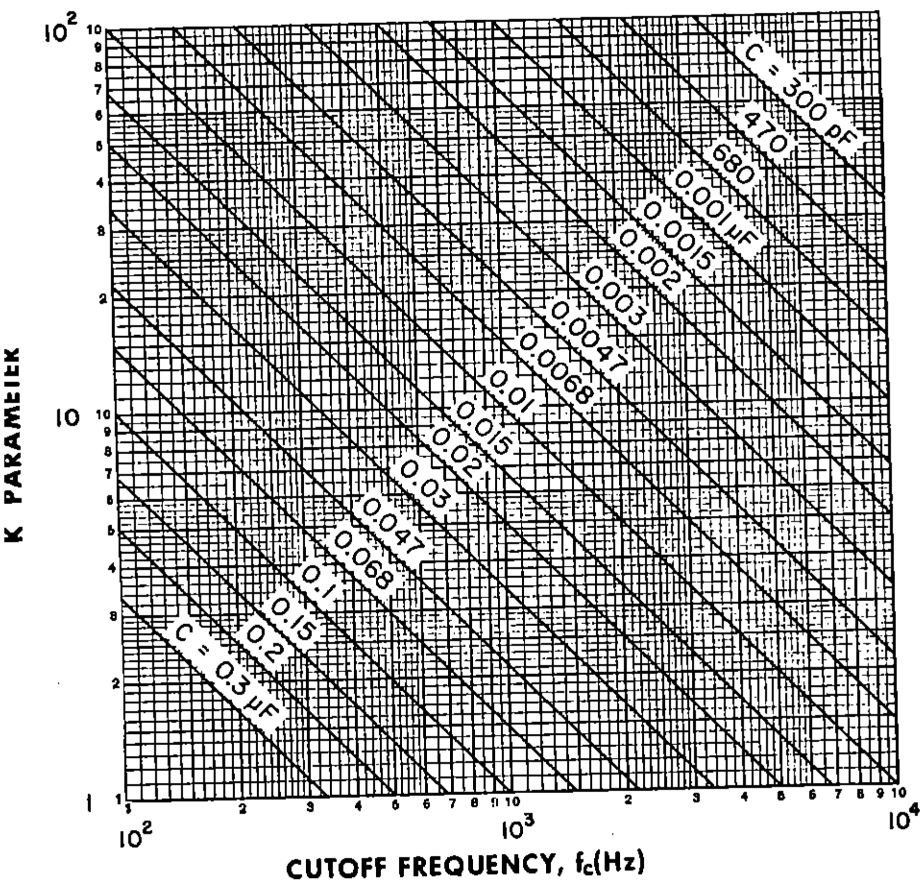


Fig. 3.6(*b*) ***K*** **parameter versus frequency.**

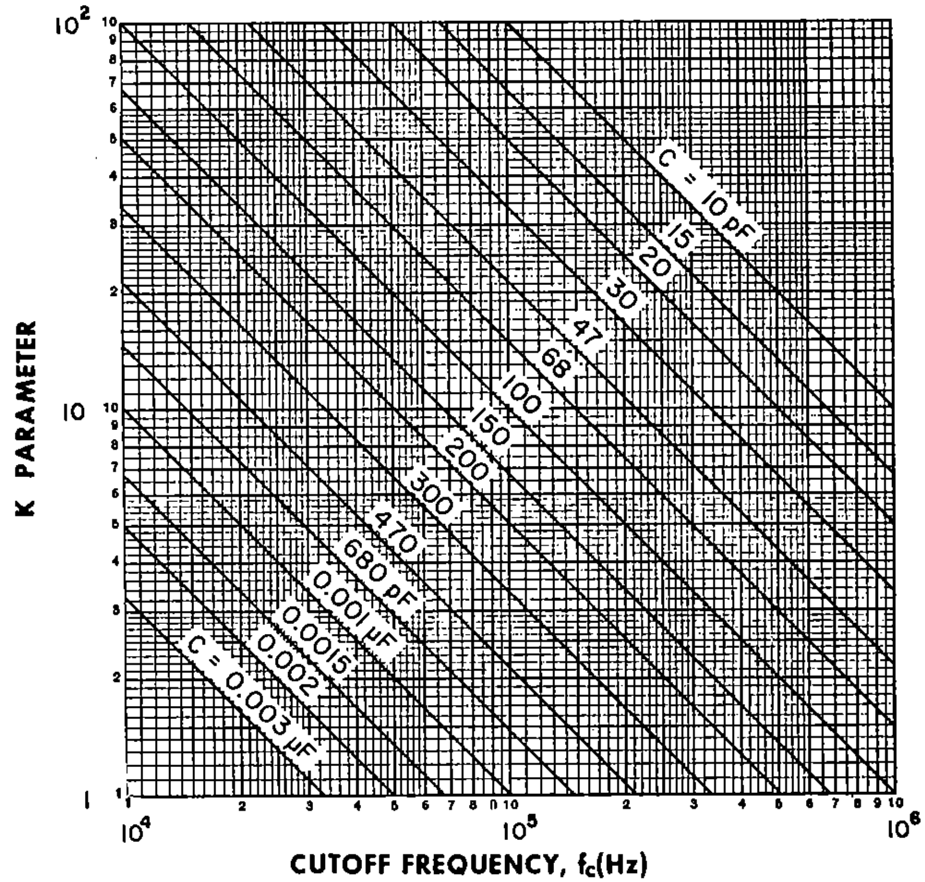


Fig. 3.6(*c*) ***K*** **parameter versus frequency.**

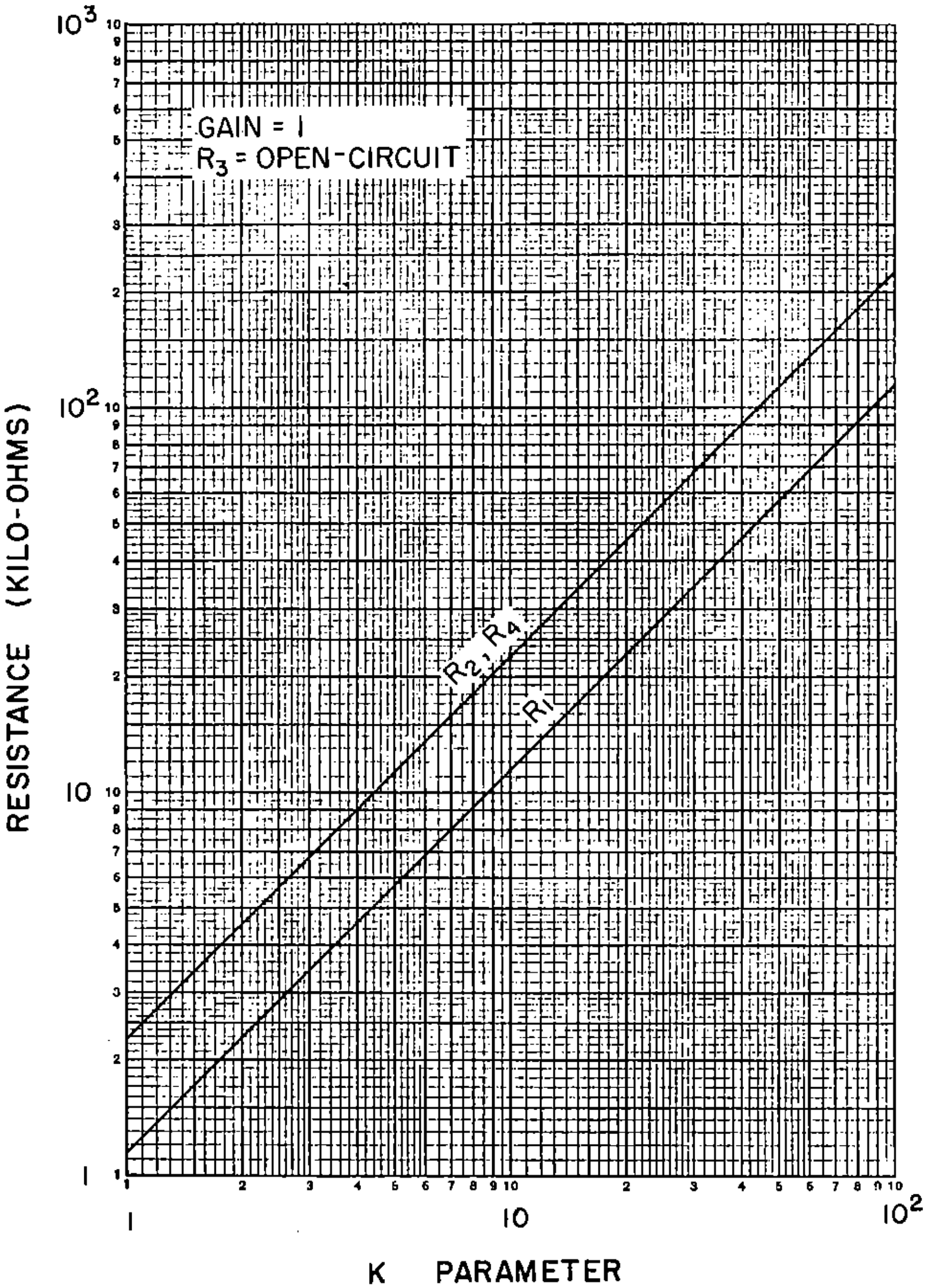


Fig. 3.7 Second-order high-pass Butterworth filter.

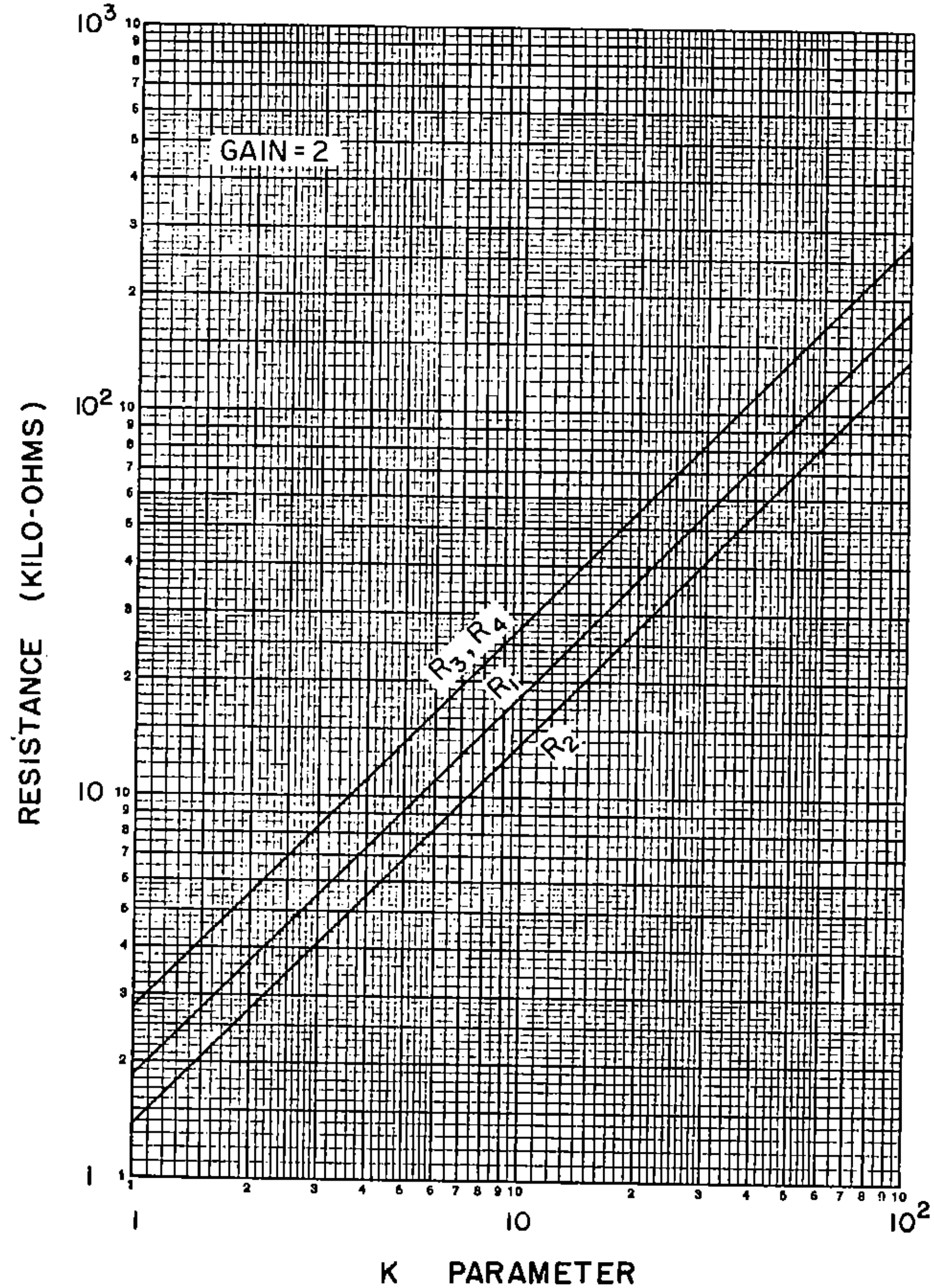


Fig. 3.8 Second-order high-pass Butterworth filter.

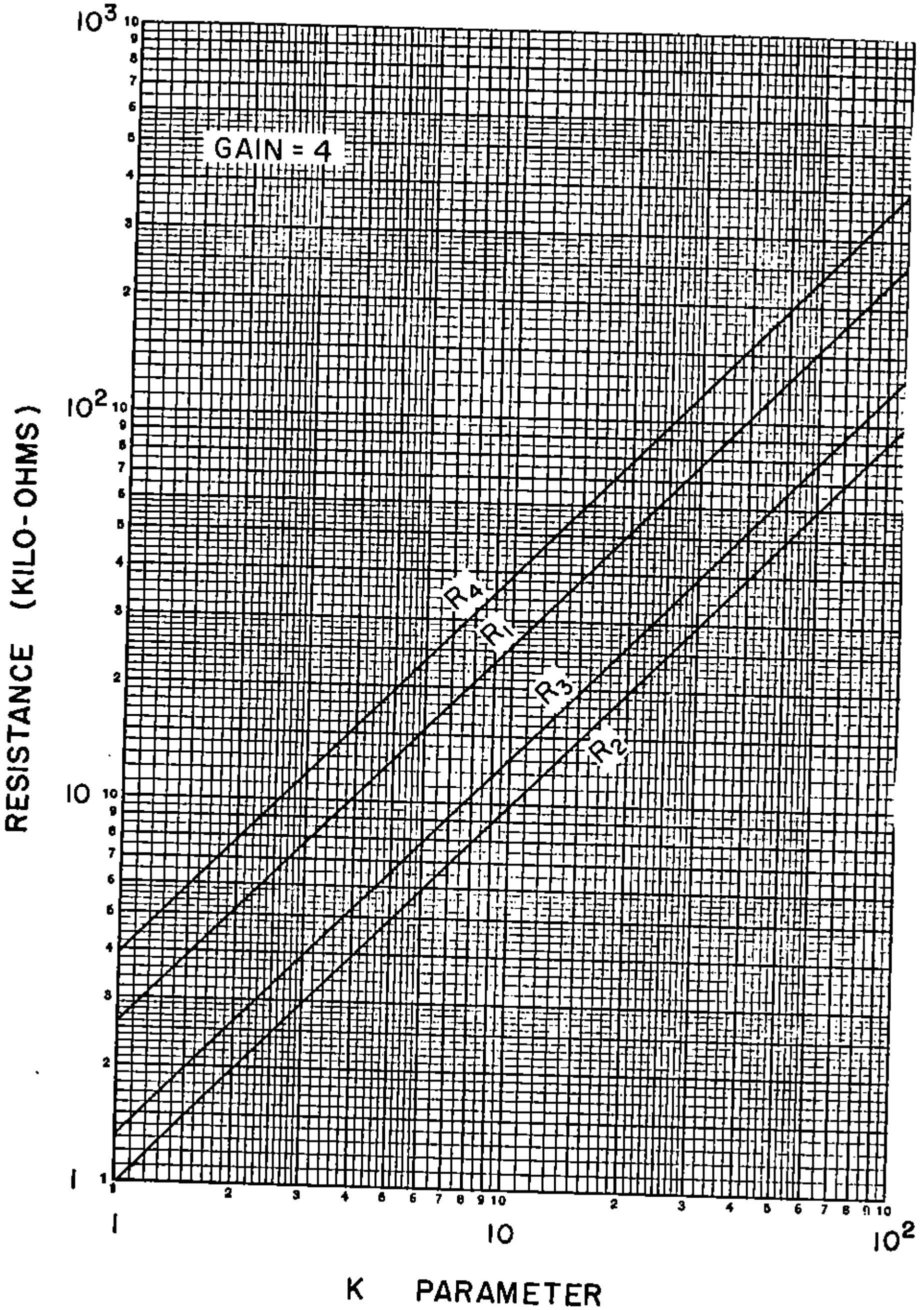


Fig. 3.9 Second-order high-pass Butterworth filter.

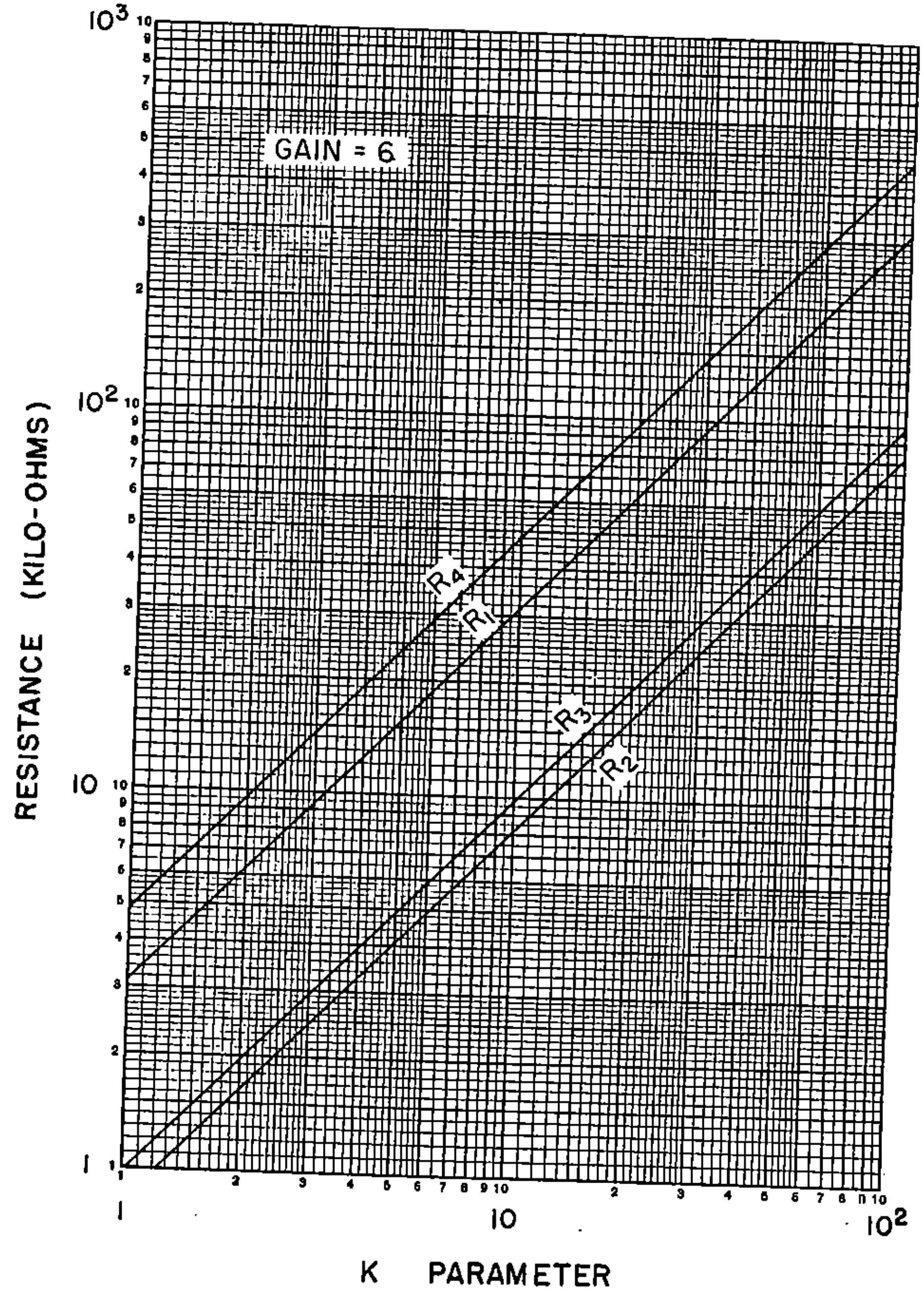


Fig. 3.10 Second-order high-pass Butterworth filter.

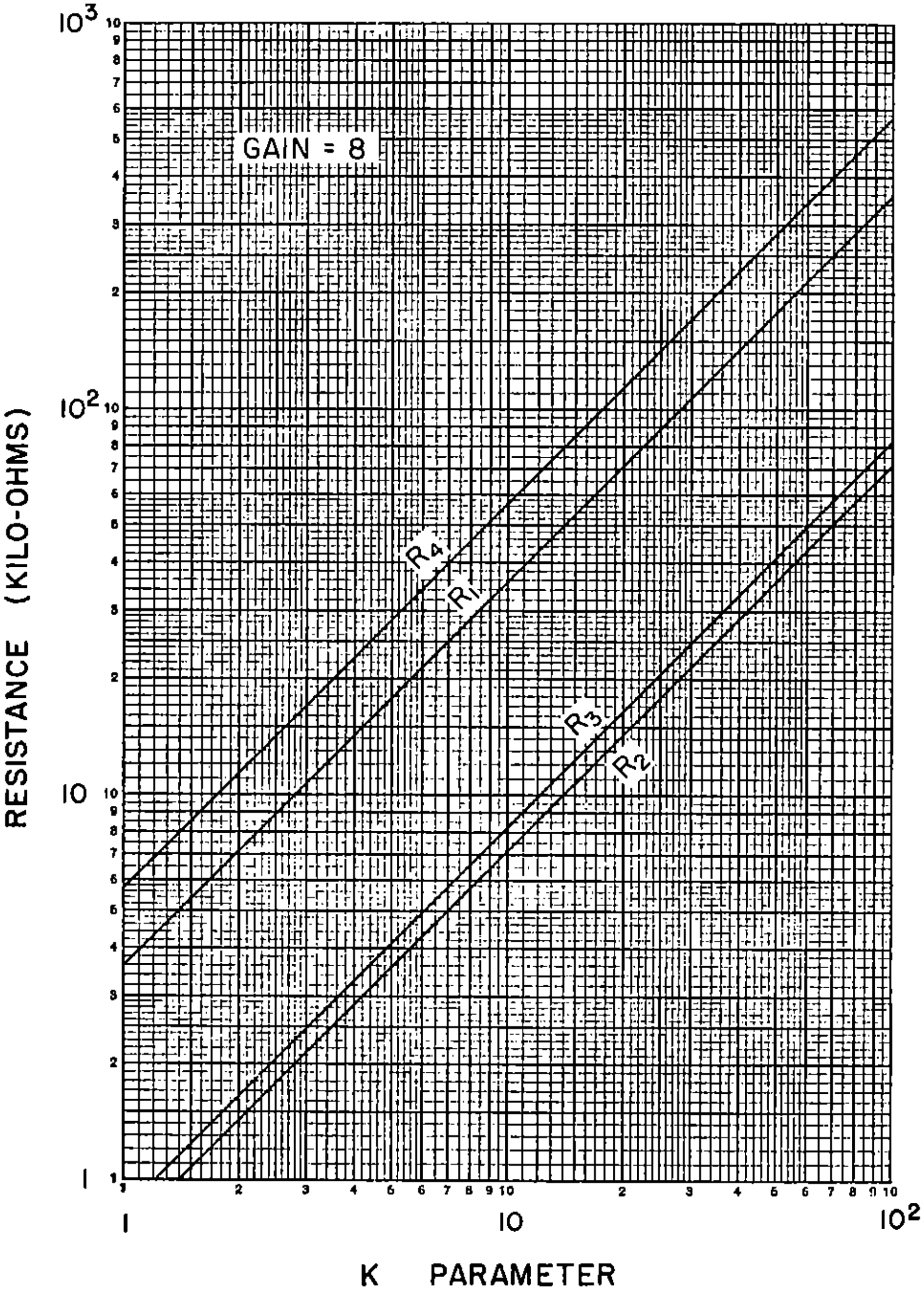


Fig. 3.11 Second-order high-pass Butterworth filter.

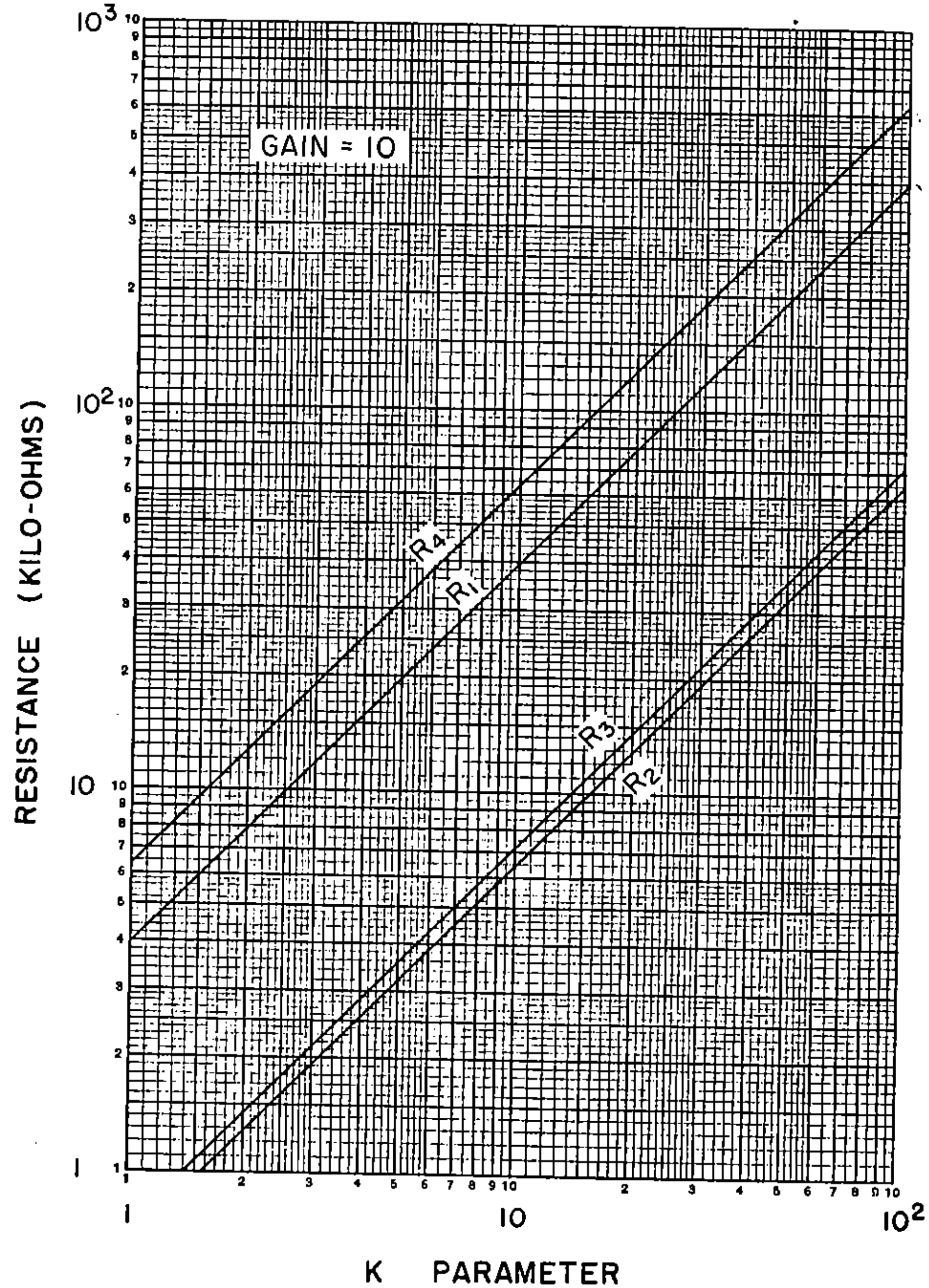


Fig. 3.12 Second-order high-pass Butterworth filter.

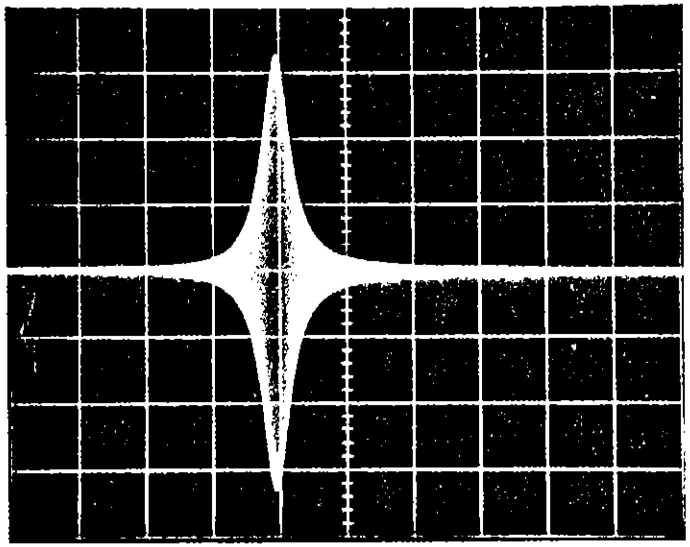
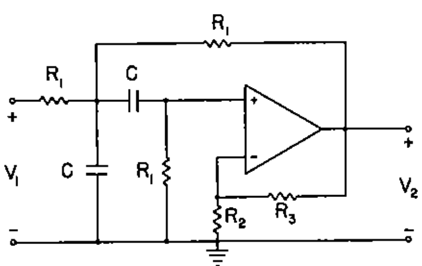


Fig. 4.11 The response of a filter with two identical stages.

Summaries of the techniques for obtaining the various practical band-pass filters are given, together with the graphs, following this section.

SUMMARY OF SECOND-ORDER VCVS BAND-PASS FILTER DESIGN PROCEDURE ($Q \leq 4$)



General circuit.

Procedure

Given f_0 (Hz), Q (or bandwidth BW in Hz), perform the following steps:

1. Select a value of capacitance C, determining a K parameter from Fig. 4.12*a* if f_0 is between 1 and $10^2 = 100$, from Fig. 4.12*b* if f_0 is between 100 and $10^4 = 10{,}000$, and from Fig. 4.12*c* if f_0 is between 10,000 and $10^6 = 1{,}000{,}000$ Hz.
2. Using this value of K, find the resistances from the appropriate one of Figs. 4.13 through 4.15, depending on Q (or BW).
3. Select standard resistances which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The remarks given for the second-order VCVS low-pass filter are applicable with the following exceptions:

(1) The statement concerning R_3 and R_4 applies to R_2 and R_3.
(2) The dc return to ground is already satisfied by R_1.
(3) Remarks concerning f_c now apply to f_0.

The center frequency f_0 can be fixed and the bandwidth (or Q) changed by varying with a potentiometer the ratio R_3/R_2. (See Sec. 4.2.)

A specific example is given in Sec. 4.2.

The values of Q, bandwidth, and gain, for N identical cascaded sections, $N = 1, 2, 3, 4$, are shown on Figs. 4.13 through 4.15.

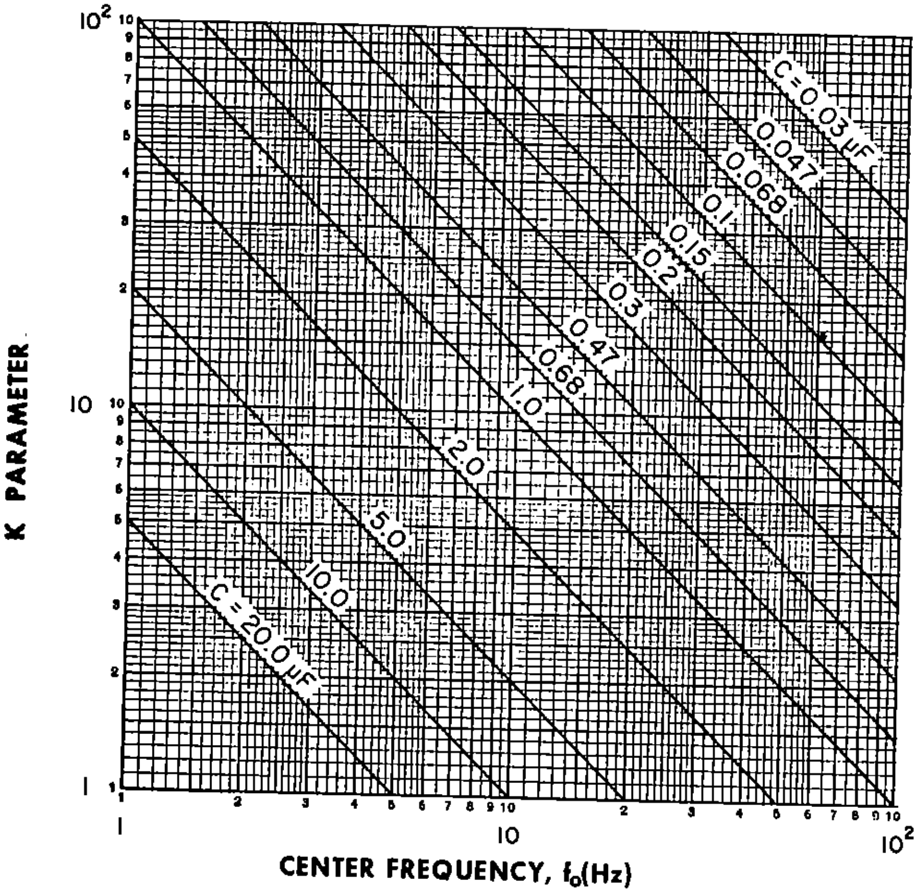


Fig. 4.12(*a*) *K* **parameter versus frequency.**

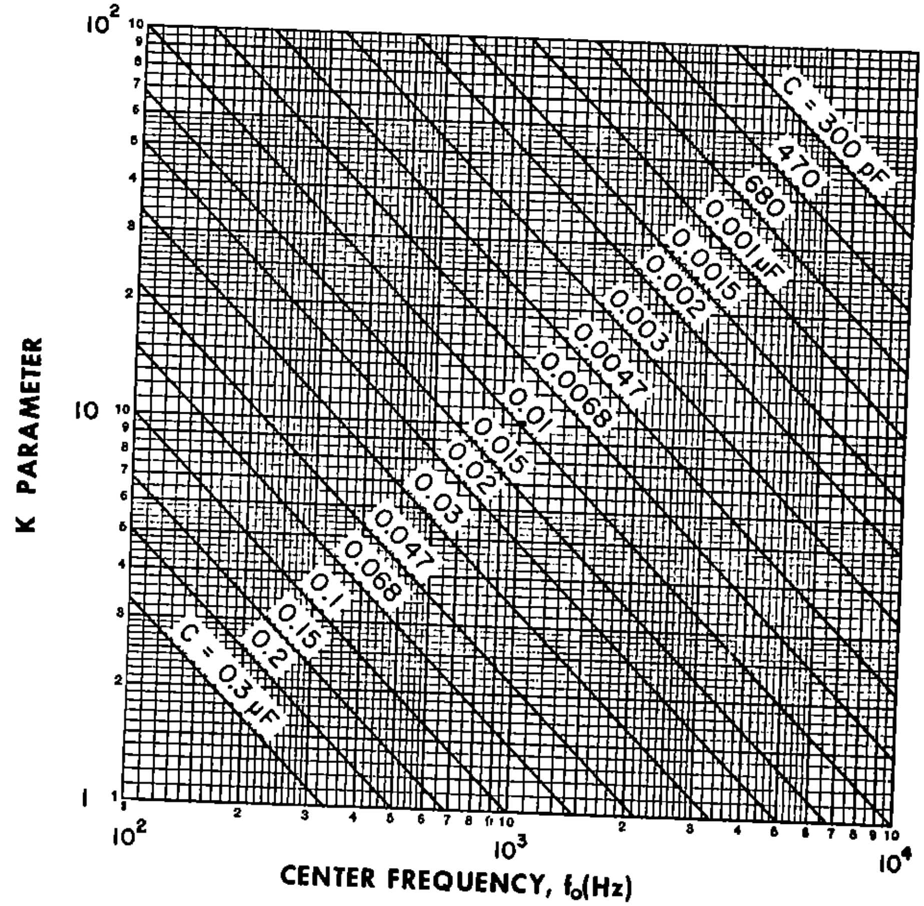


Fig. 4.12(*b*) *K* **parameter versus frequency.**

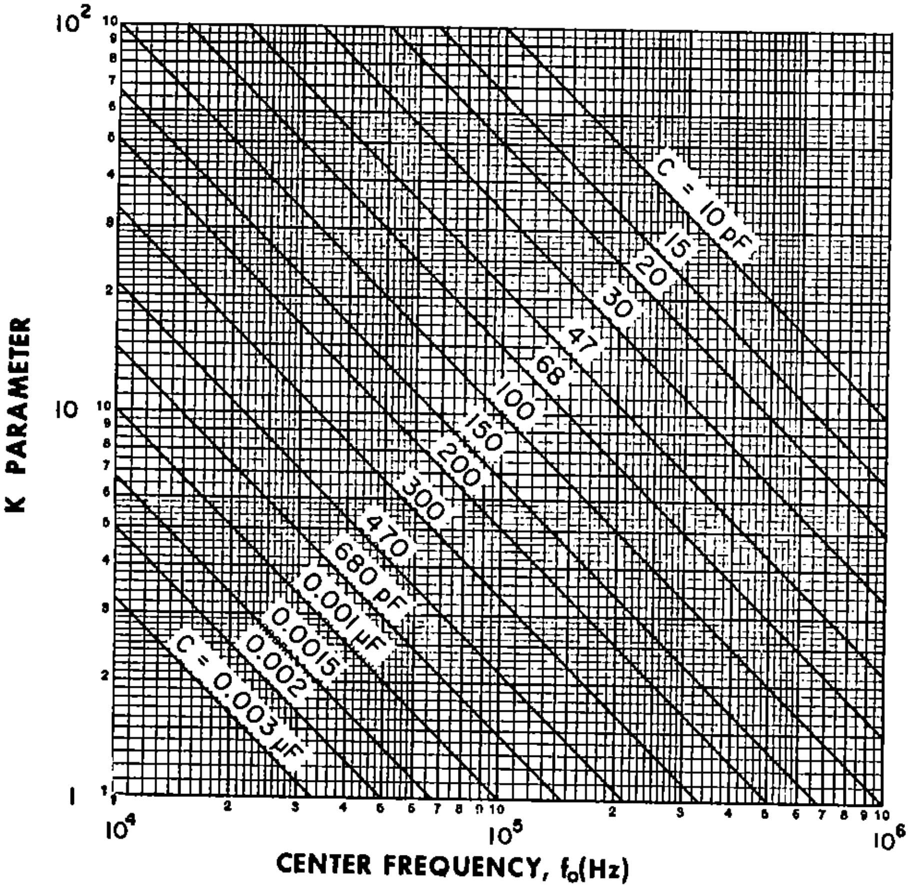
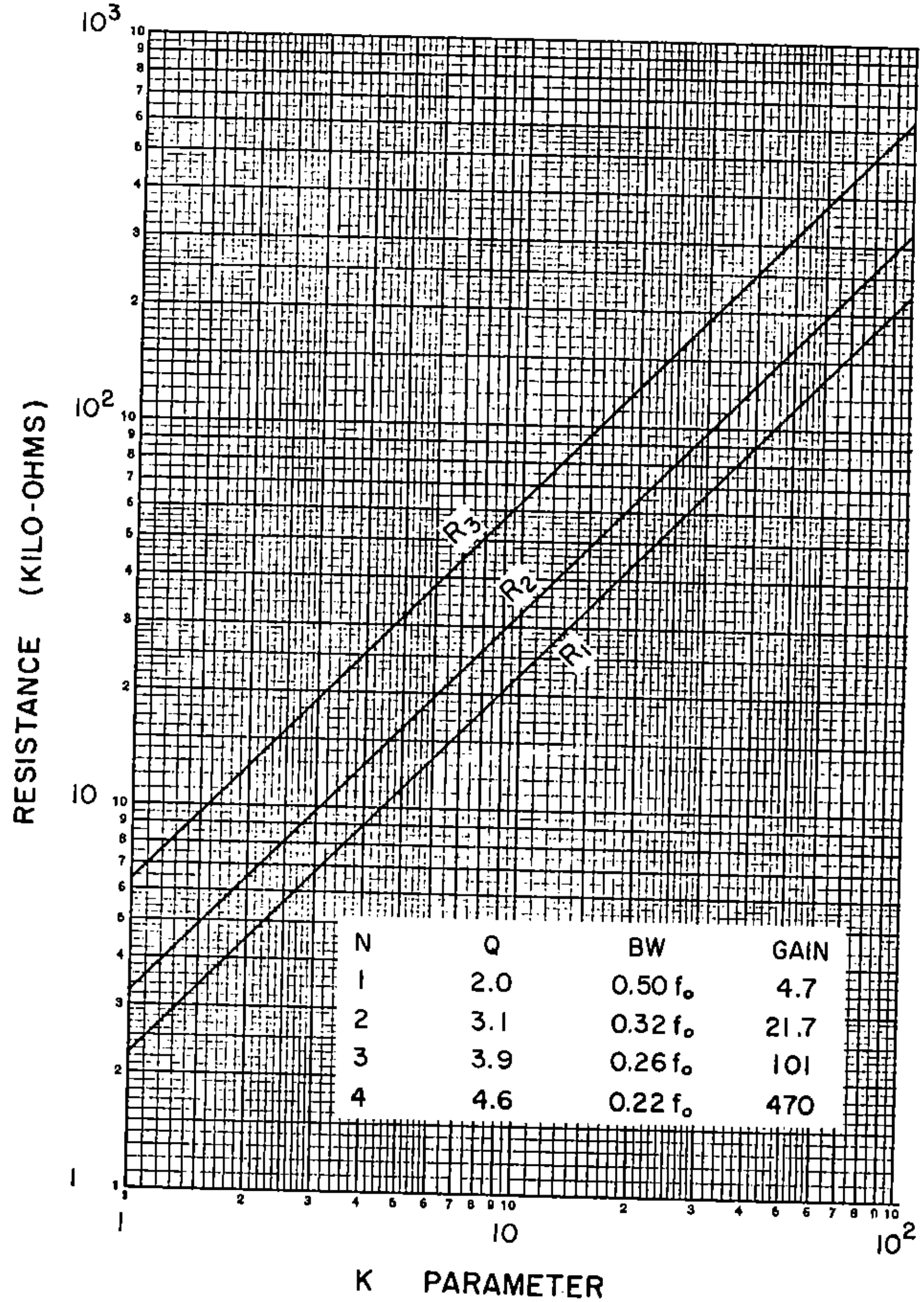


Fig. 4.12 (*c*) *K* parameter versus frequency.



N	Q	BW	GAIN
1	2.0	0.50 f_o	4.7
2	3.1	0.32 f_o	21.7
3	3.9	0.26 f_o	101
4	4.6	0.22 f_o	470

Fig. 4.13 VCVS band-pass filter.

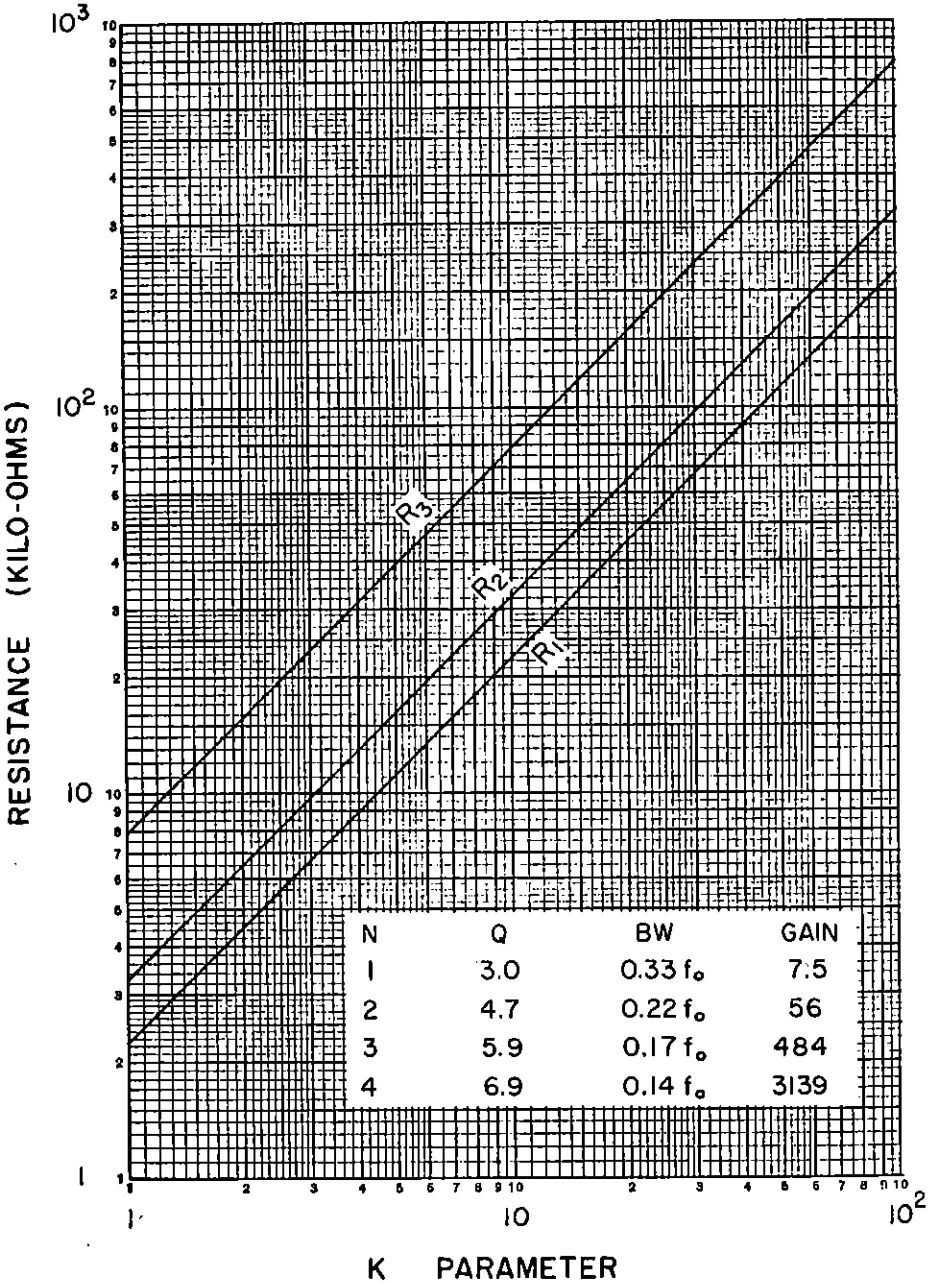


Fig. 4.14 VCVS band-pass filter.

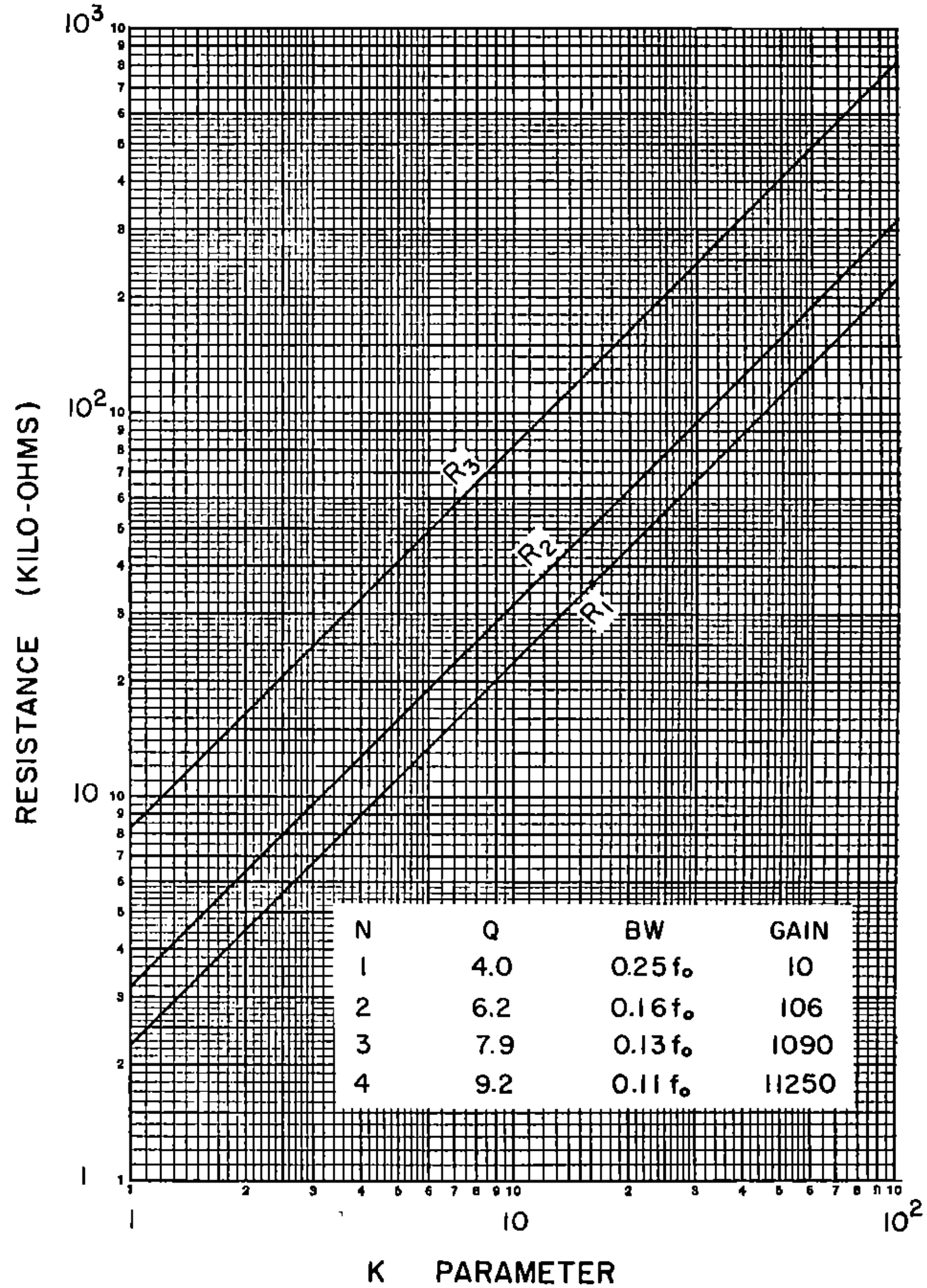
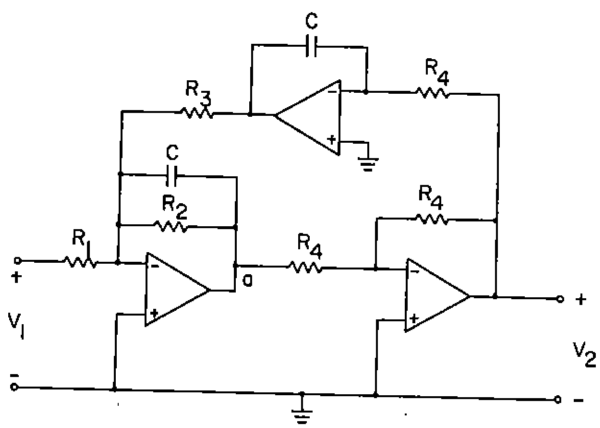


Fig. 4.15 VCVS band-pass filter.

SUMMARY OF SECOND-ORDER BIQUAD BAND-PASS FILTER DESIGN PROCEDURE ($Q \leq 100$)



General circuit.

Procedure

Given f_0 (Hz), Q (or bandwidth BW in Hz), and gain, perform the following steps:

1. Select a value of capacitance C and determine a K parameter from Fig. 4.12*a*, *b*, or *c*, as described for the second-order VCVS band-pass filter.
2. Using this value of K and the values of Q (f_0/BW) and the gain, find the resistances from Fig. 4.41.
3. Select standard resistances which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The remarks given for the second-order VCVS low-pass filter are applicable, except that there are three op-amps rather than one, f_c should be replaced by f_0, and there is no resistance ratio for use in minimizing the dc offsets. Also, the dc return to ground requirement is satisfied by resistors R_2 and R_3. Finally, in the remark relative to the slew rate, f_c should be replaced by f_u, the highest frequency of the passband.

The gain is R_2/R_1. If an inverting gain of the same magnitude is desired, the output may be taken at node *a*.

The filter response is readily adjusted by varying R_1, R_2, and R_3. Varying R_1 affects the gain, varying R_2 affects Q, and varying R_3 affects f_0.

The biquad band-pass filter is discussed in Sec. 4.5.

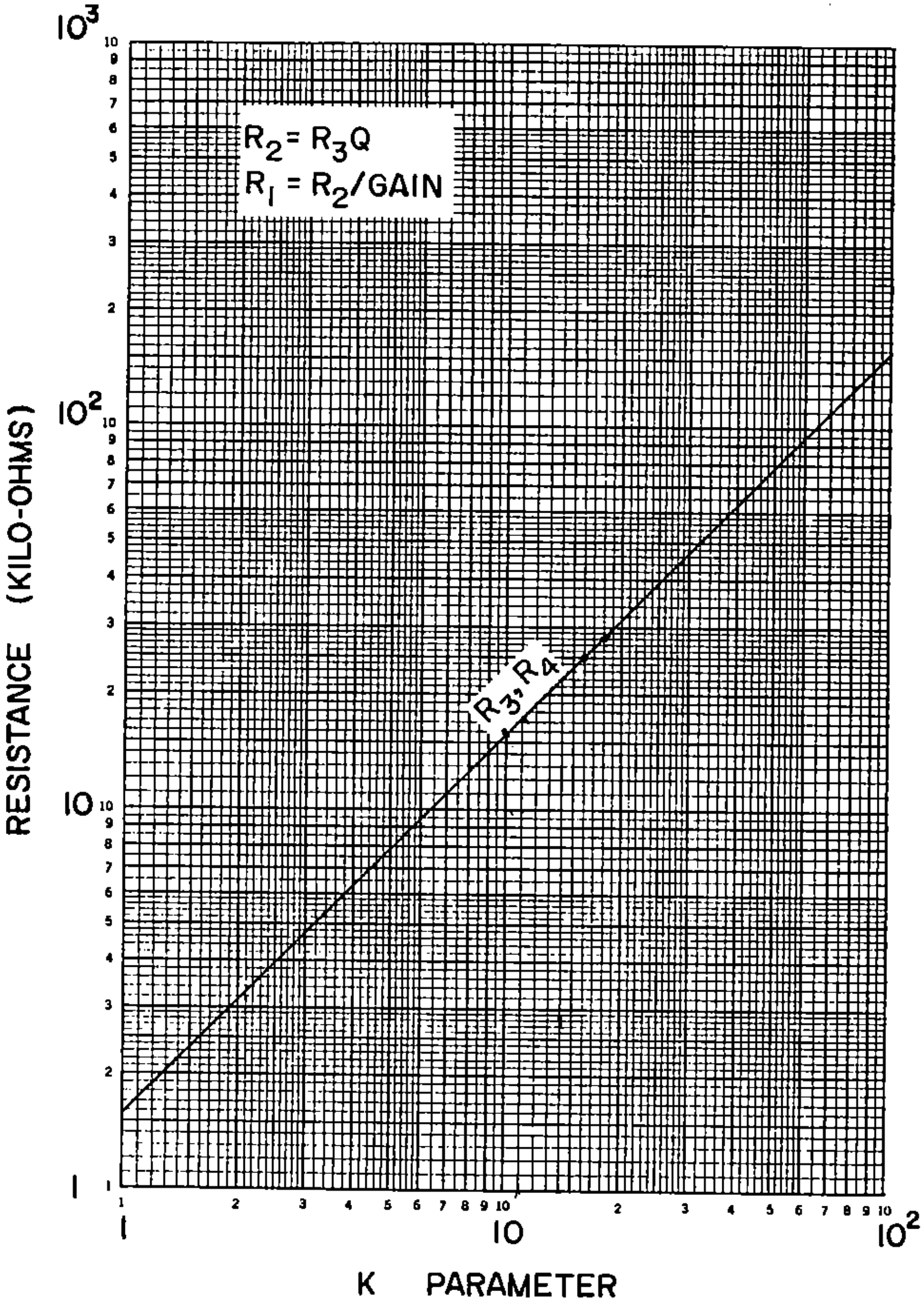


Figure 4.41 Biquad band-pass filter.

SUMMARY OF HIGHER ORDER BAND-PASS FILTER DESIGN PROCEDURE

(*a*) $Q \leq \sqrt{2} = 1.414$

This may be accomplished by cascading a second-order low-pass filter with cutoff f_{c2} and a second-order high-pass filter with cutoff $f_{c1} < f_{c2}$. For best results the frequency f_{c2} should be at least twice f_{c1}. The procedure is described in the summaries for the second-order low- and high-pass filters.

This results in a center frequency of approximately $f_0 = \sqrt{f_{c1}f_{c2}}$ (it is exactly this if the two are both Butterworth filters), with a gain slightly less than the product of the gains of the two stages. The bandwidth is approximately $f_{c2} - f_{c1}$. (For higher Q, one could use fourth-order stages.)

(*b*) $Q \geq \sqrt{2} = 1.414$

This may be done by cascading two or more second-order band-pass filters as described in the summary sheets in this chapter.

The result is a higher Q (more narrow BW) as given by Fig. 4.10, and a gain approximately equal to the product of the section gains. The center frequency should be that of a single stage.

where ω_0 is the center frequency in rad/sec and $B = \omega_0/Q$ is the width of the band rejected. The gain is defined as the value of $H(s)$ at either zero or infinity and is seen to be K.

A circuit which realizes Eq. (5.1) is the band-reject circuit shown in Fig. 5.2 [28], an analysis of which yields, if $R_3R_4 = 2R_1R_5$,

$$B = \frac{2}{R_4C}$$
$$\omega_0^2 = \frac{1}{R_4C^2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{5.2}$$

and an inverting gain of magnitude R_6/R_3.

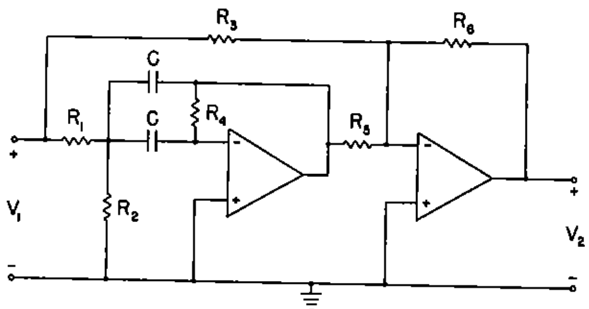


Fig. 5.2 A band-reject filter.

We may obtain a practical realization of the band-reject filter of Fig. 5.2, for given values of center frequency f_0, Q, and gain as described in the summary.

As an example, suppose we want $f_0 = 60$ Hz, $Q = 10$, with a gain of 10. From Fig. 5.4*a*, we see that if we choose a capacitance value of $C = 0.1\ \mu$F, then the K parameter is 16.6. Using this value of K, we find from Fig. 5.12, for a gain of 10, that the other element values are $R_1 = 131$ kΩ, $R_2 = 1.34$ kΩ, $R_3 = 16$ kΩ, $R_4 = 525$ kΩ, $R_5 = 33$ kΩ, and $R_6 = 165$ kΩ. Using standard values of 130, 1.3, 16, 510, 33, and 160 kΩ, we obtain the filter whose amplitude response is shown in Fig. 5.3. The scale used is 10 Hz/division, starting at 10 Hz. The actual results are $f_0 = 59.3$ Hz, $Q = 9.4$ ($B = 6.3$ Hz), and a gain of 10.

A summary of the techniques for obtaining a practical band-reject filter is given, together with the appropriate graphs, following this section.

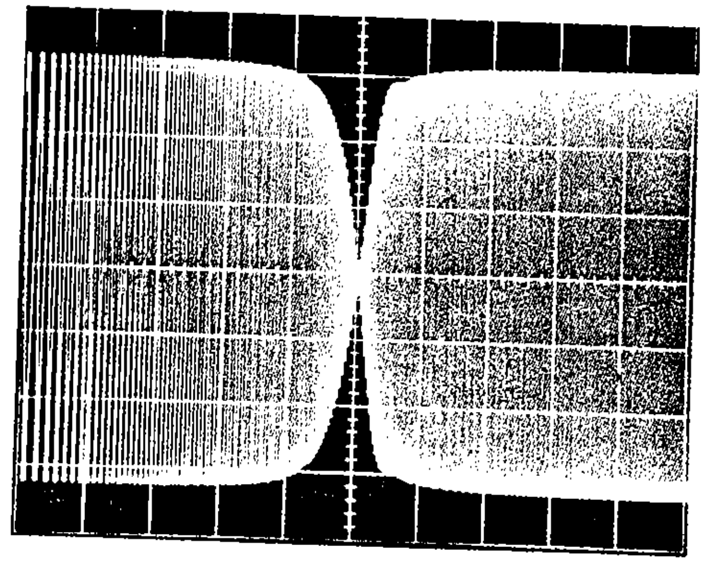
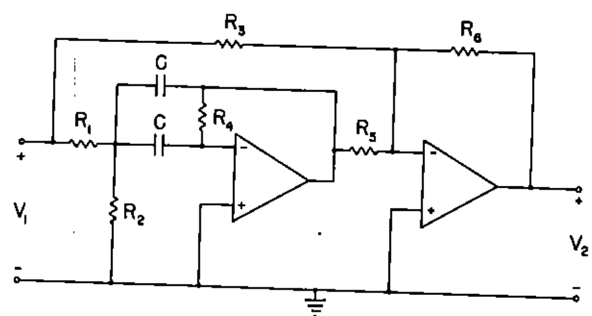


Fig. 5.3 A band-reject filter response.

SUMMARY OF BAND-REJECT FILTER DESIGN PROCEDURE



General circuit.

Procedure

Given f_0 (Hz), Q (or bandwidth BW), and gain, perform the following steps:

1. Select a value of capacitance C and determine a K parameter from Fig. 5.4*a* for f_0 between 1 and $10^2 = 100$, Fig. 5.4*b* for f_0 between 100 and $10^4 = 10{,}000$, and Fig. 5.4*c* for f_0 between 10,000 and $10^6 = 1{,}000{,}000$ Hz.
2. Using this value of K, find the resistances from the appropriate one of Figs. 5.5 through 5.13, depending on Q (or BW) and the gain.
3. Select standard resistances which are as close as possible to those indicated on the graph and construct the circuit.

Comments and Suggestions

The remarks given for the second-order VCVS low-pass filter are applicable with the following exceptions:

(1) The statement concerning the ratio R_4/R_3 is not applicable.
(2) The dc returns to ground are already satisfied by R_4 and R_6.
(3) Remarks concerning f_c now apply to f_0.
(4) The open-loop gain of the op-amps should be at least 50 times the square root of the filter gain.

Q, and hence BW, can be varied to some degree, without appreciably changing f_0, by varying R_4. Changing C slightly changes f_0 slightly. For minimum dc offset, one may place, in the noninverting input leads of the op-amps, resistances equal to R_4 and $R_5R_6/(R_5 + R_6)$ respectively.

A specific example is given in Sec. 5.1.

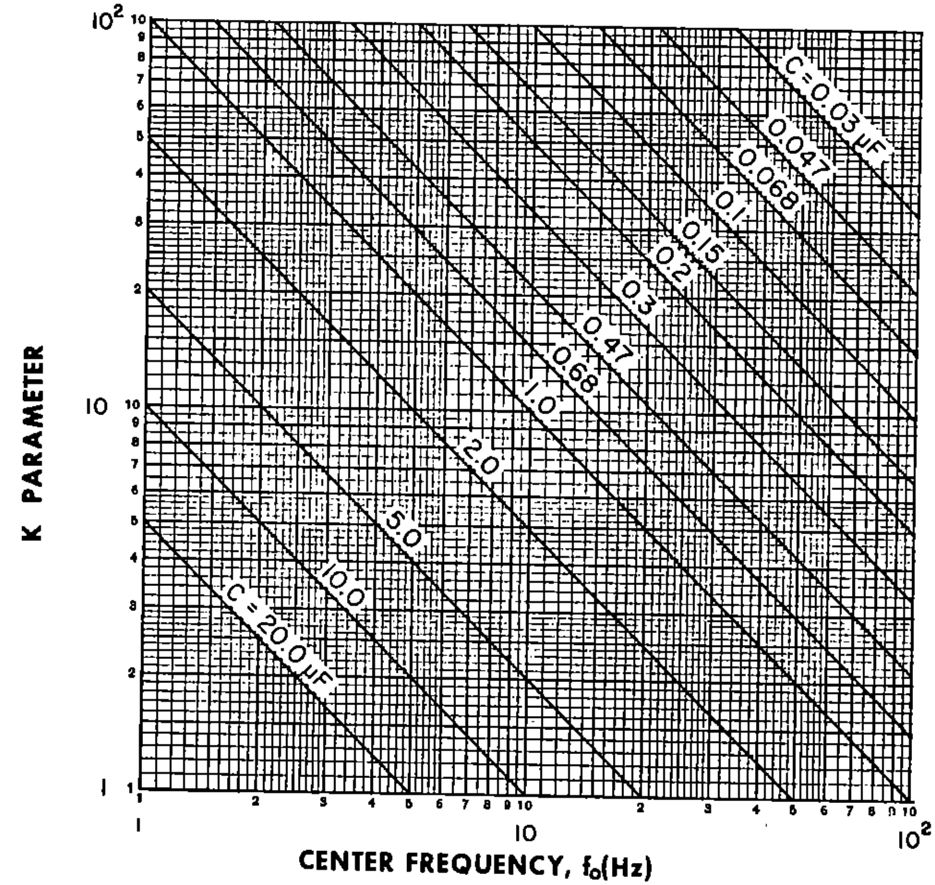


Fig. 5.4(*a*) *K* parameter versus frequency.

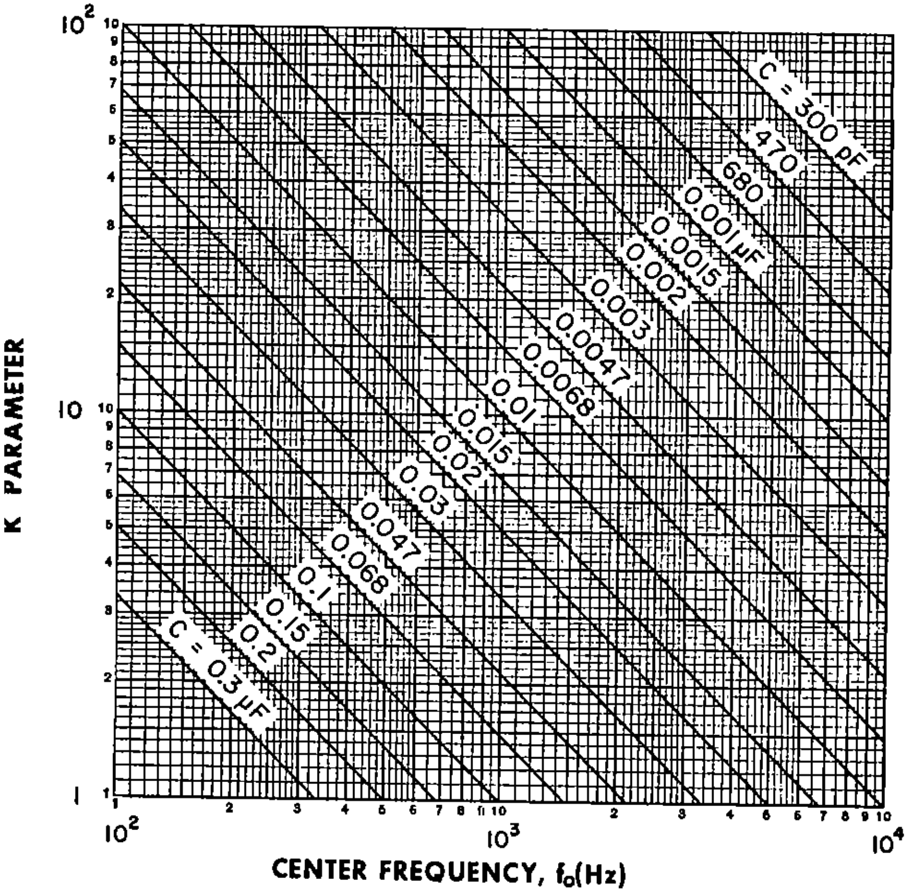


Fig. 5.4(*b*) *K* parameter versus frequency.

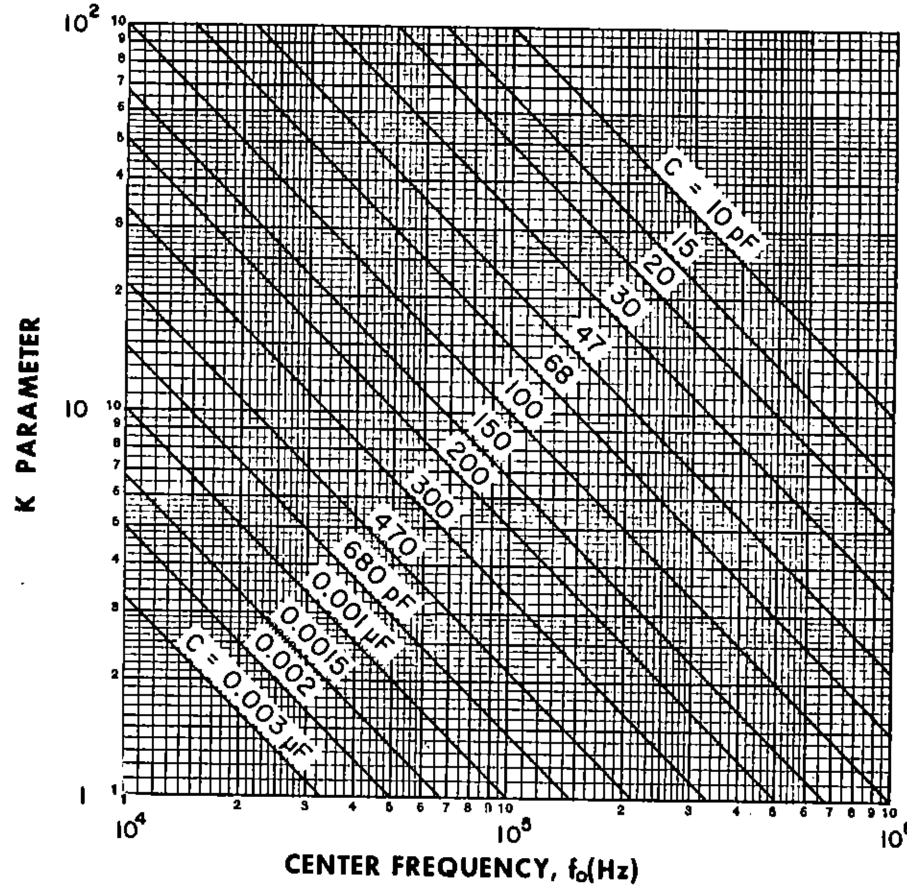


Fig. 5.4(*c*) *K* parameter versus frequency.

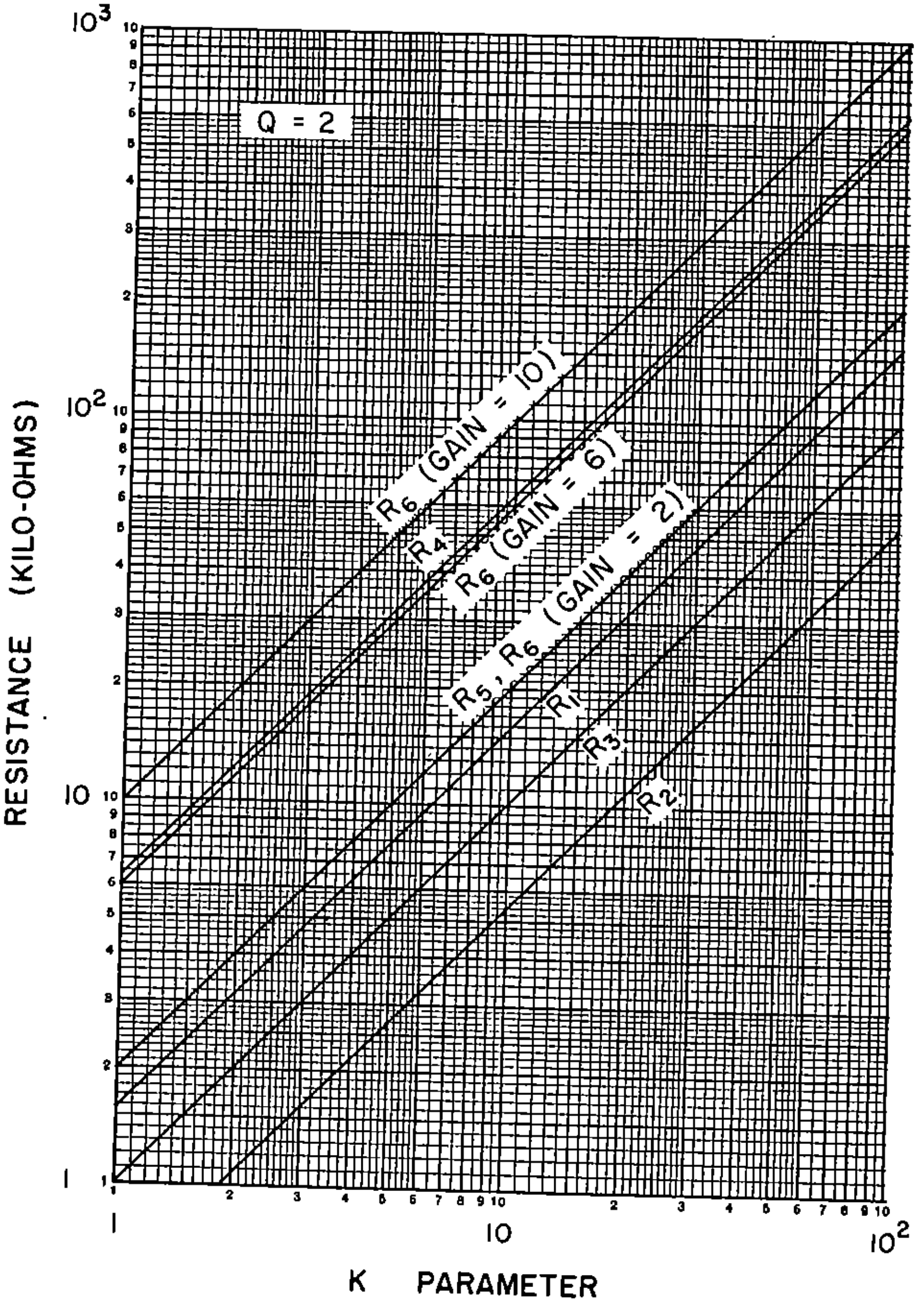


Fig. 5.5 Band-reject filter.

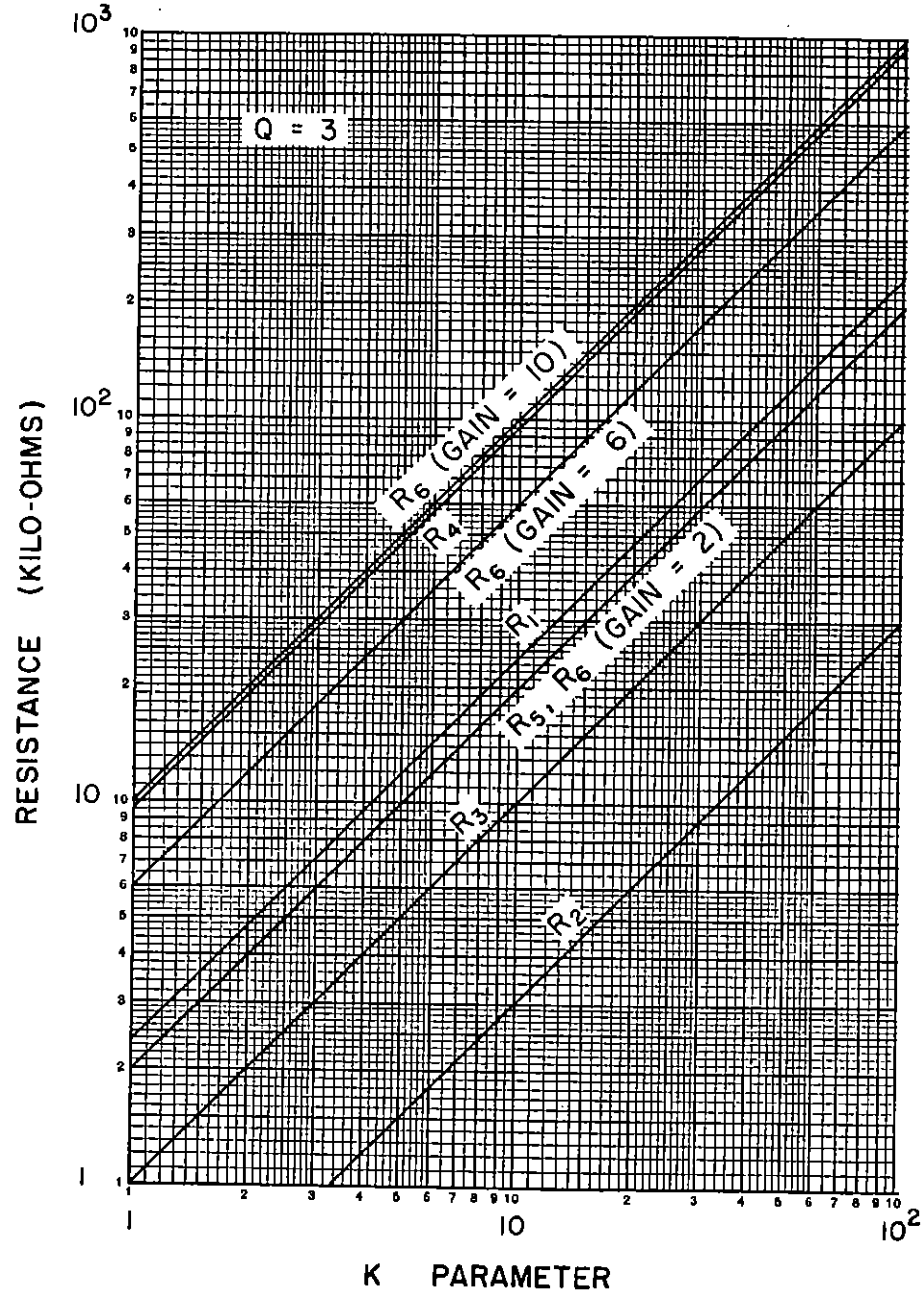


Fig. 5.6 Band-reject filter.

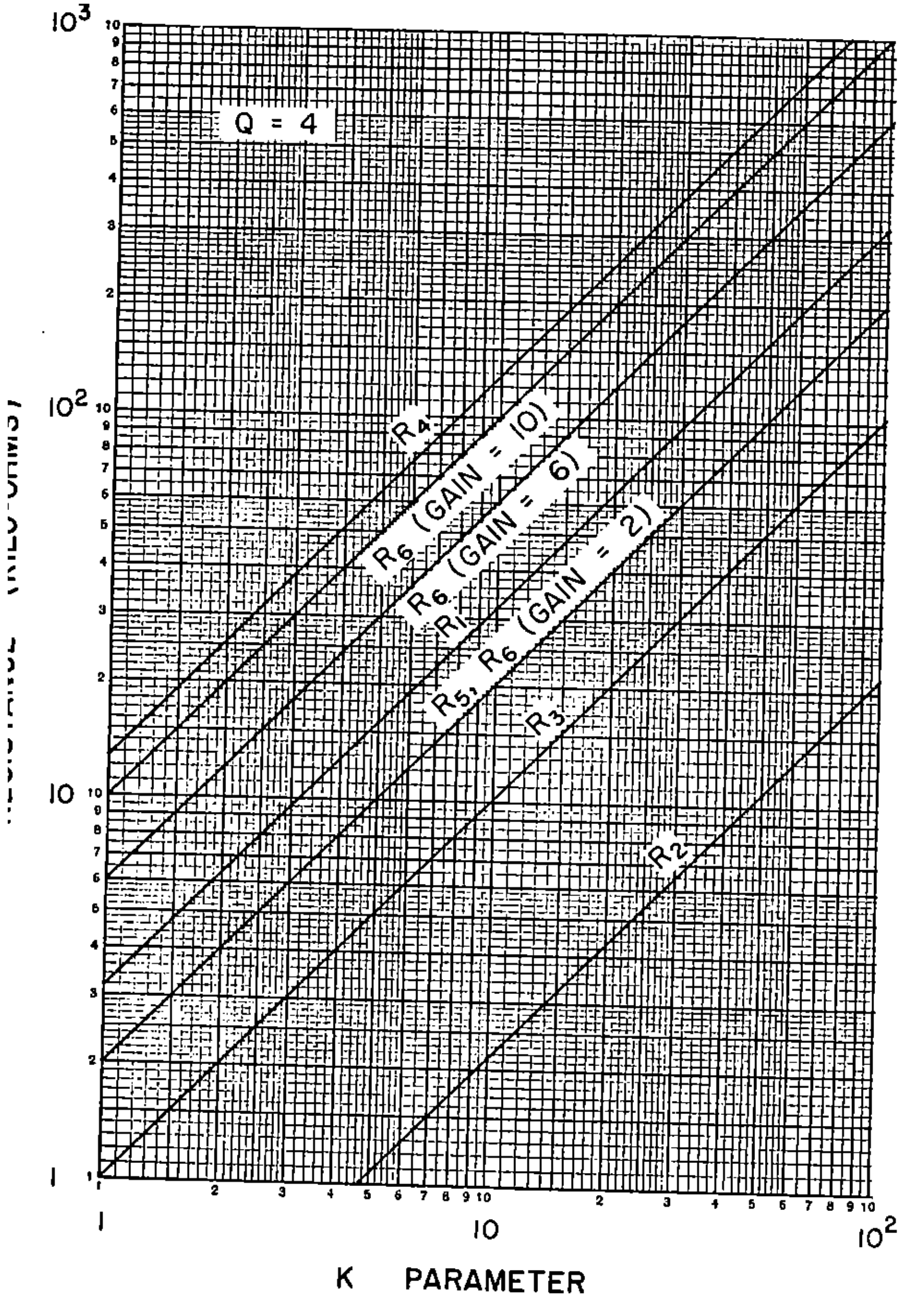


Fig. 5.7 Band-reject filter.

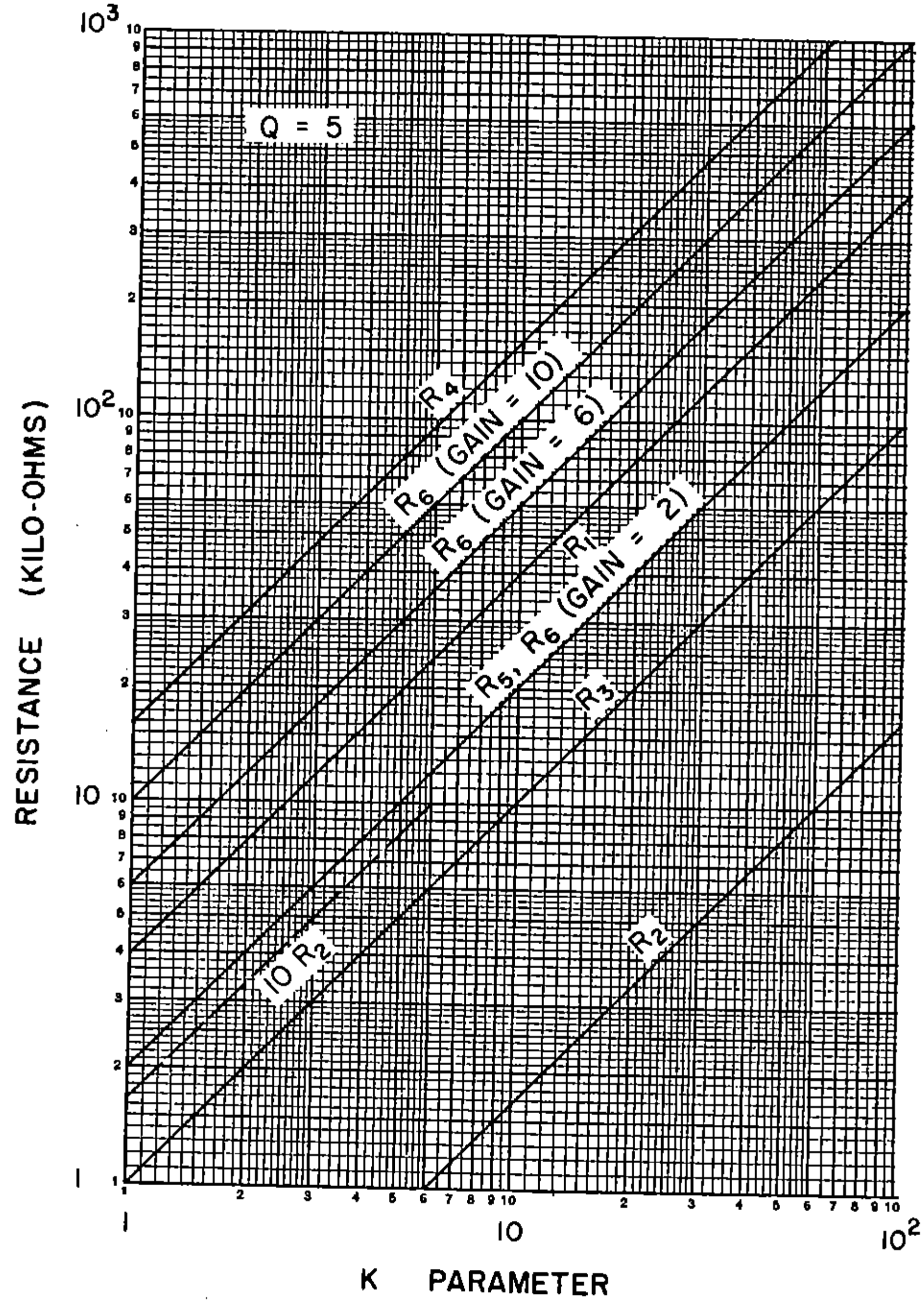


Fig. 5.8 Band-reject filter.

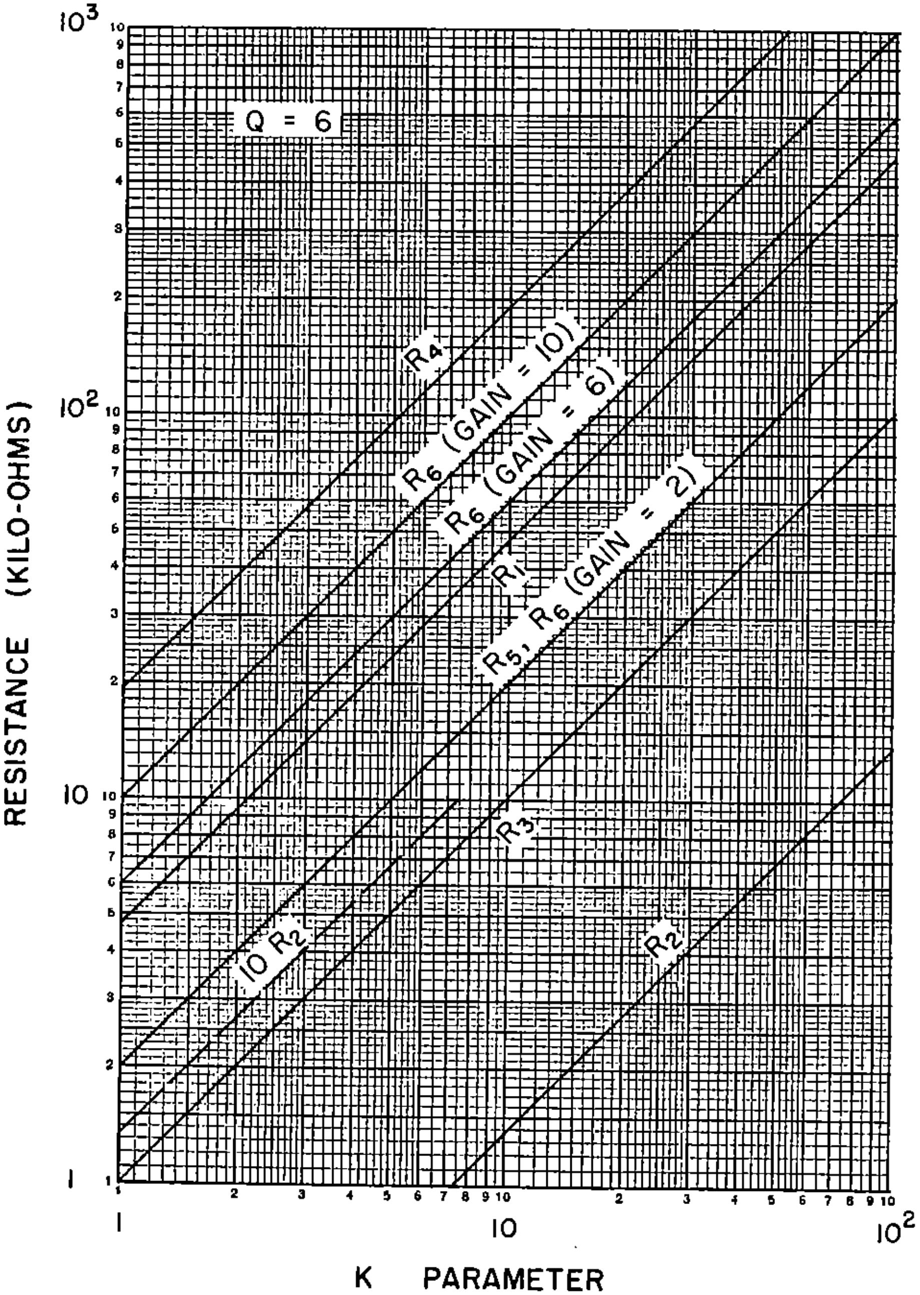


Fig. 5.9 Band-reject filter.

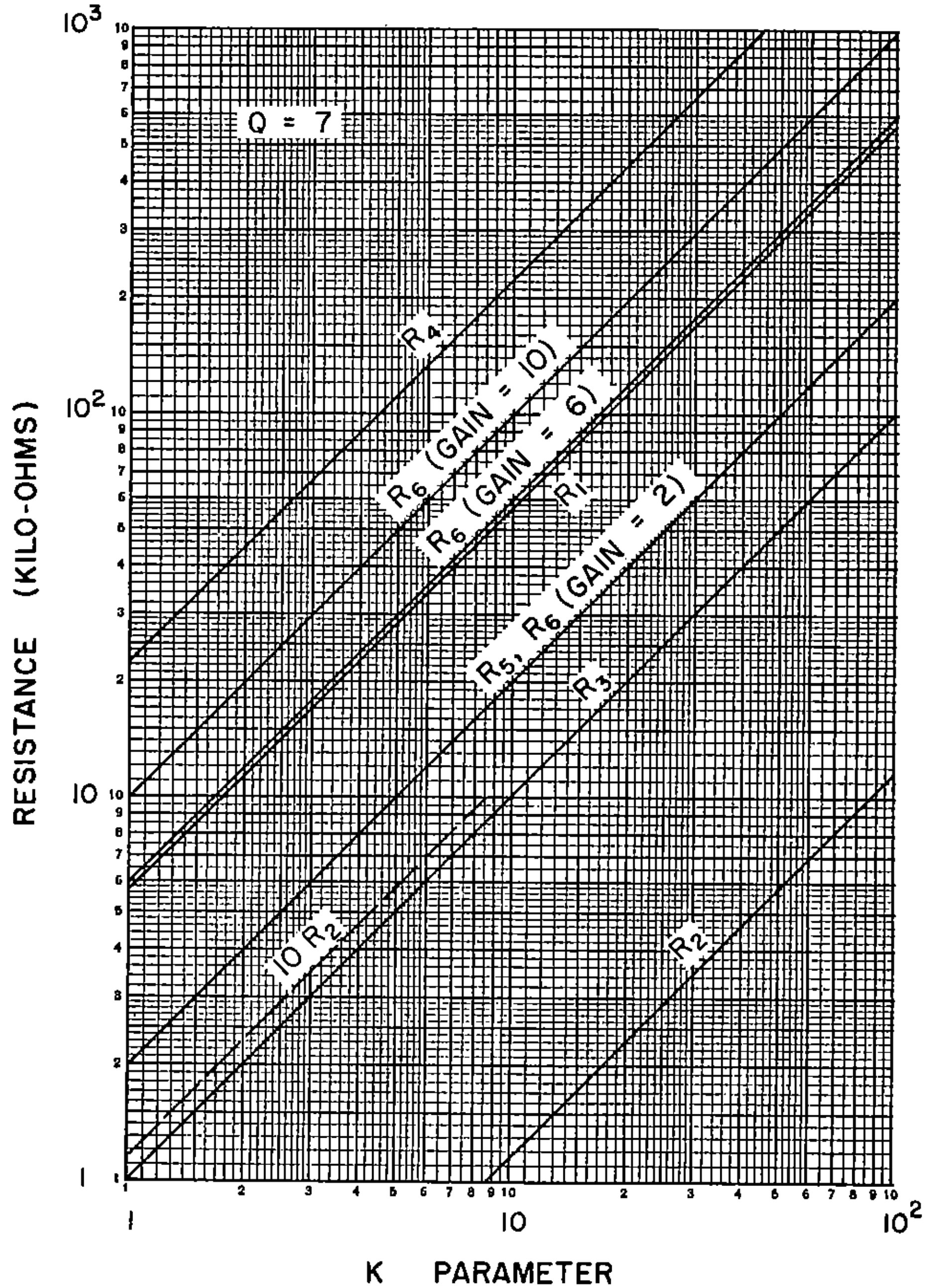


Fig. 5.10 Band-reject filter.

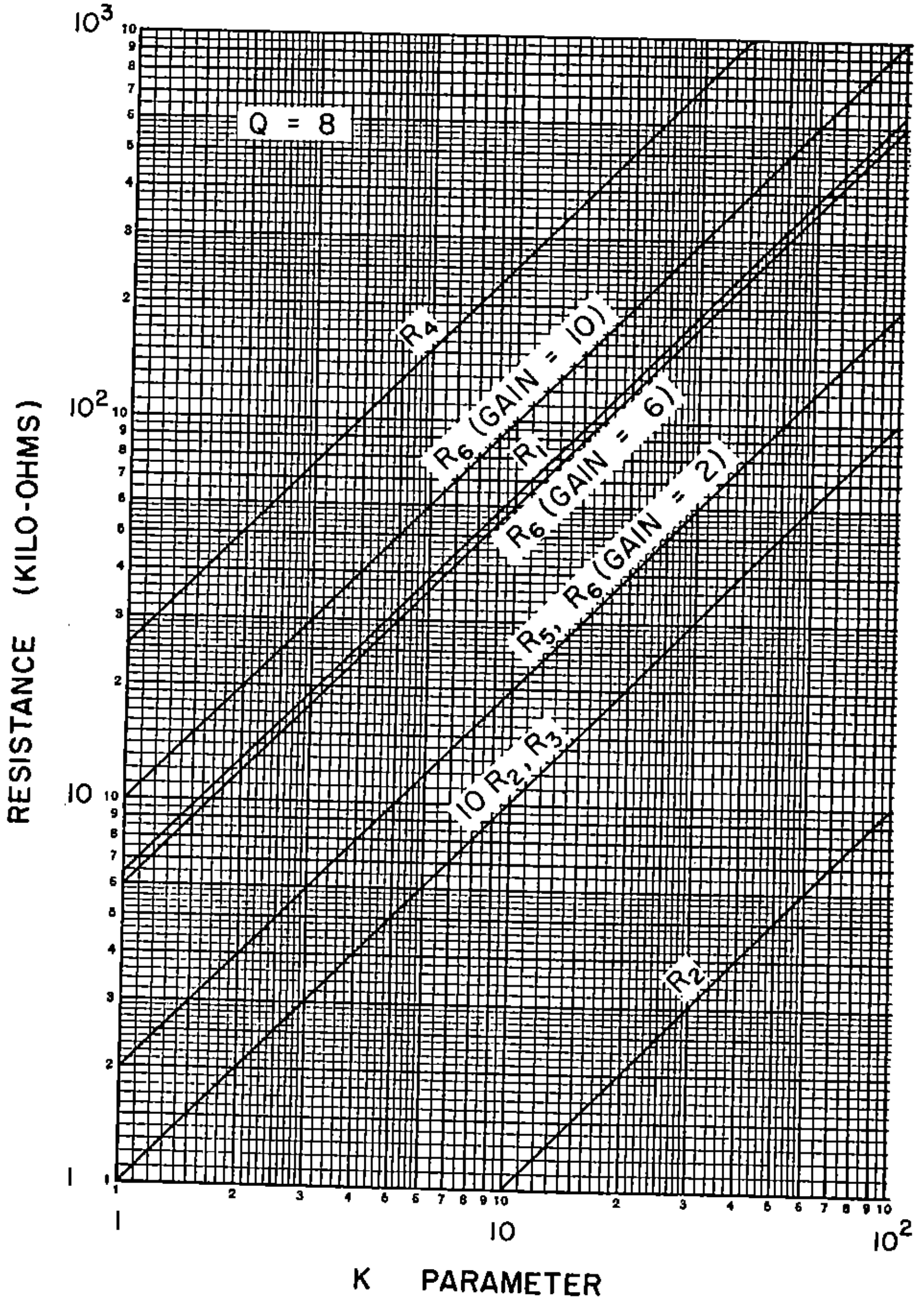


Fig. 5.11 Band-reject filter.

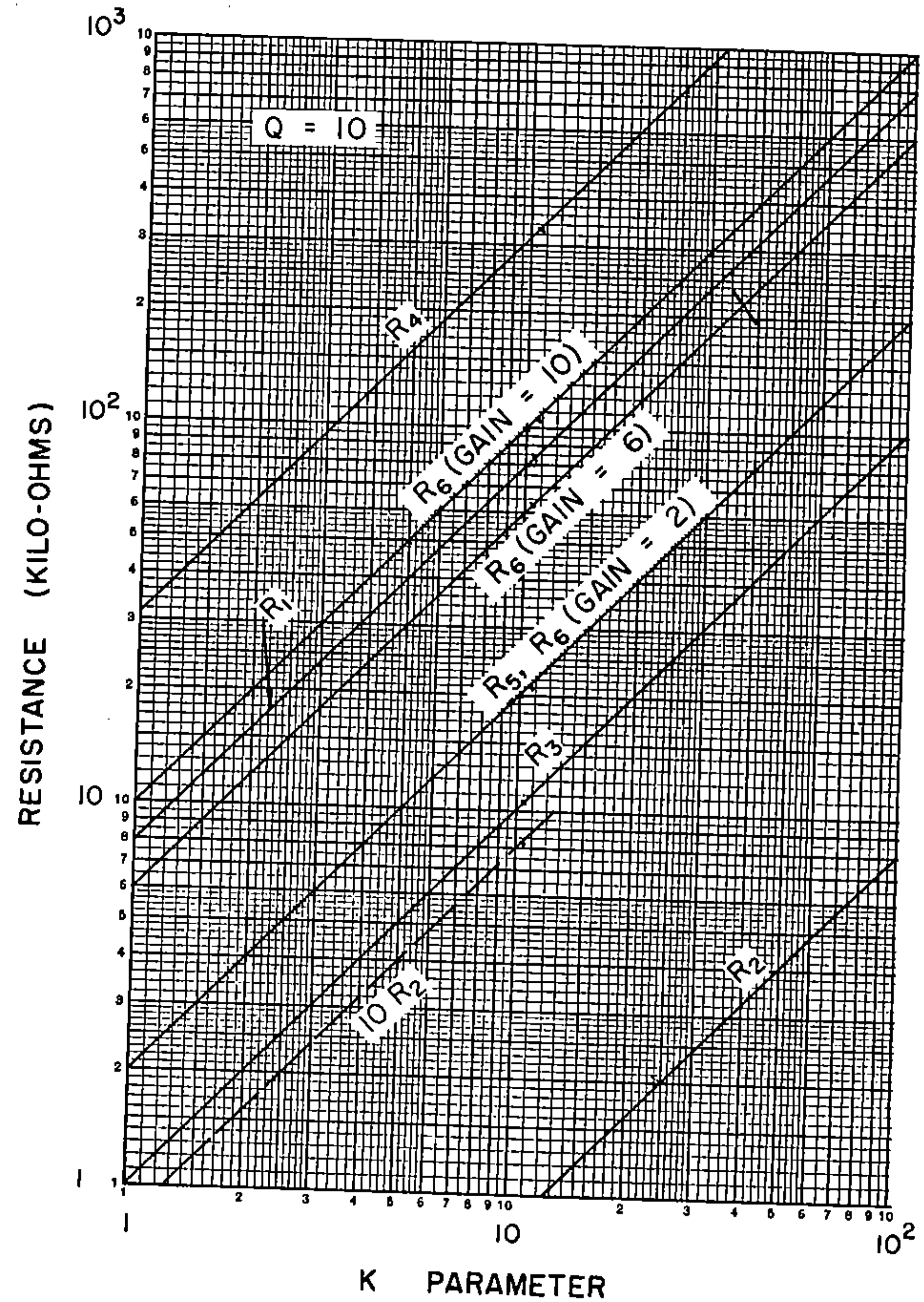


Fig. 5.12 Band-reject filter.

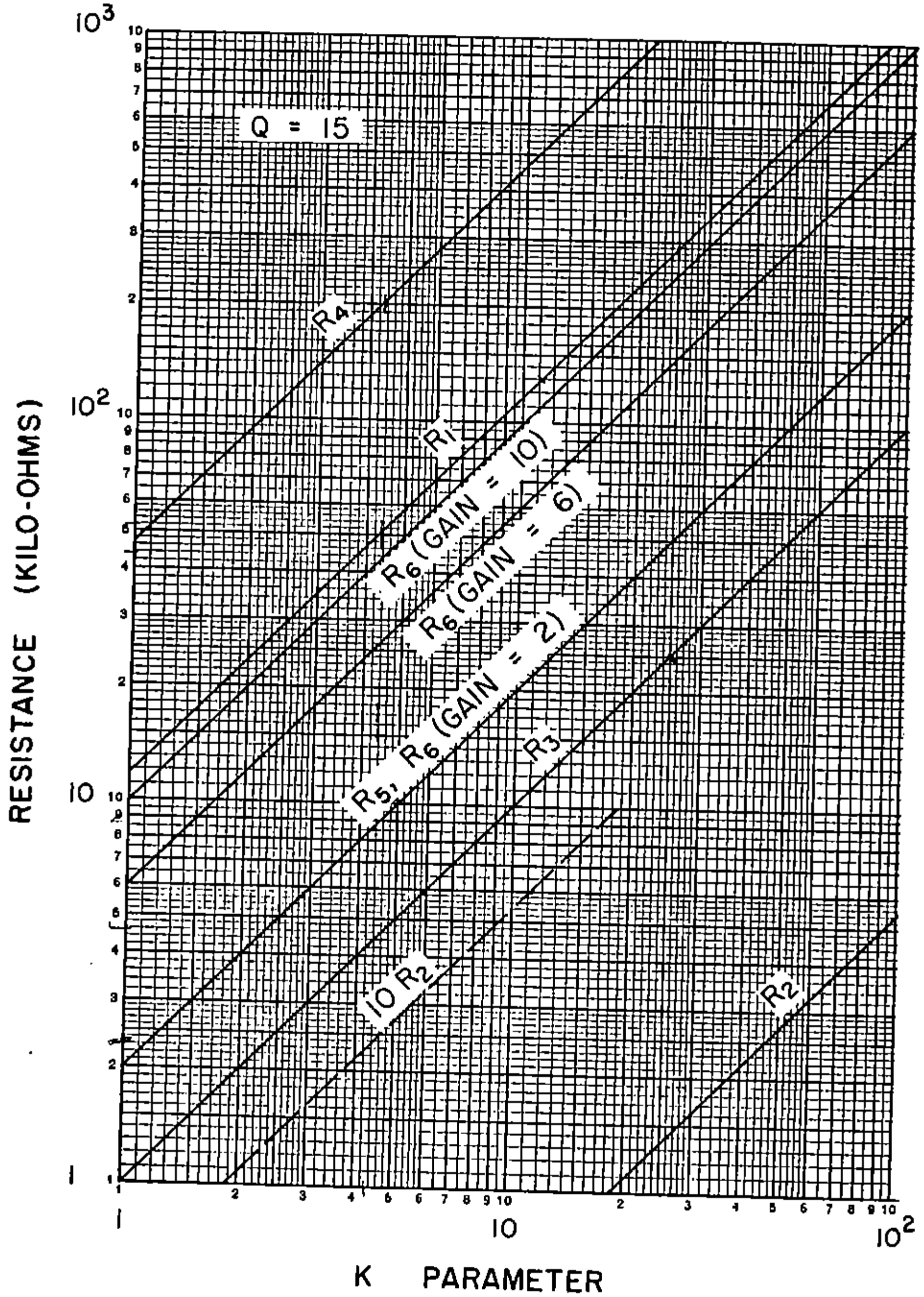


Fig. 5.13 Band-reject filter.

6 PHASE-SHIFT AND TIME-DELAY FILTERS

6.1 All-Pass (Phase-Shift) Filters

An all-pass, or phase-shifting, filter is one which passes signals of all frequencies equally well while changing or shifting their phase by some prescribed amount. Since shifting a frequency by some negative amount is equivalent to delaying that component by some positive time as it passes through the filter, the all-pass filter may also be thought of as a time-delay circuit. The phase shift or time delay of its transfer function varies with frequency as the amplitude remains essentially fixed over the useful range of frequencies.

Our transfer functions are ratios of output to input voltages, V_2/V_1. At ω_0 (or in Hz, f_0), if the phase shift is a negative number, say $\phi(\omega_0) = -\phi_0$ degrees, then at ω_0 the phase of the input V_1 is greater than that of the output V_2 by ϕ_0 degrees. Thus, if the two waveforms are viewed simultaneously, the input wave reaches its peaks or dips ϕ_0 degrees before the output wave reaches its peaks or dips. Therefore the input signal is leading the output signal by ϕ_0 degrees. Also the difference in time in seconds between a peak or dip of the input wave and the immediately preceding peak or dip of the output wave, when the amplitudes of the two waves are plotted versus time, is the time delay. Evidently a phase shift of $-\phi_0$ is equivalent to a phase shift of $360° - \phi_0$. For example, if the input wave leads the output by 270° ($\phi = -\phi_0 = -270°$), then it may also be said that the input leads by $-90°$ ($\phi = -\phi_0 = +90°$), in which case the output leads by $+90°$.

The amplitude response of the transfer function of an all-pass filter is ideally constant for all frequencies and in a practical realization should be very nearly constant over the range of operation. The phase response might typically look like that of Fig. 6.1, which is plotted for $0 \geq \phi \geq -360°$. One should remember that these values are equivalent to values obtained