Active and Passive Filters as Loudspeaker Crossover Networks*

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This tutorial paper defines the function of a crossover network and then explores methods of meeting this function. For moderately priced two-way loudspeakers, a passive network at about 800–1600 Hz will continue to dominate the designs of the future. However, the use of active filters (electronic crossover networks) and buffer amplifiers offers the most significant means of loudspeaker improvement in the next decade. As one typical factor, crossover frequencies need to be lowered and crossover slopes increased, and the active filter is the only economical method of doing this.

INTRODUCTION: The crossover or frequency dividing network plays a most important role in the performance of high-quality loudspeaker systems. To date, individual drivers have not been capable of reproducing all frequencies present in music that are detectable by the human ear. The crossover network is a particular type of filter that allows various drivers, each suited to a particular range of frequencies in the audio spectrum, to be combined into a system capable of wide frequency coverage. The function of the crossover network then is simply to divide the frequency spectrum so that signals of the appropriate frequency range are directed to the appropriate driver of a multidriver loudspeaker system.

We have noted in the past a strong tendency to separate the filter problem from the overall loudspeaker system problem; consequently, some rather poor systems have been designed. As a symptom of the general ignorance of the system aspects of the crossover problem, consider the fact that most networks marketed separately do not specify the slope of the system transfer characteristic in the stop band. As a result, the novice tends to visualize a stone wall at a certain magic point in the frequency spectrum with tones to the left and to the right of this stone wall obediently marching off to their respective drivers. It seems a shame to destroy this illusion by noting that a filter with a stop band defined by a square corner and infinite slope is a classic example of a physically nonrealizable filter.

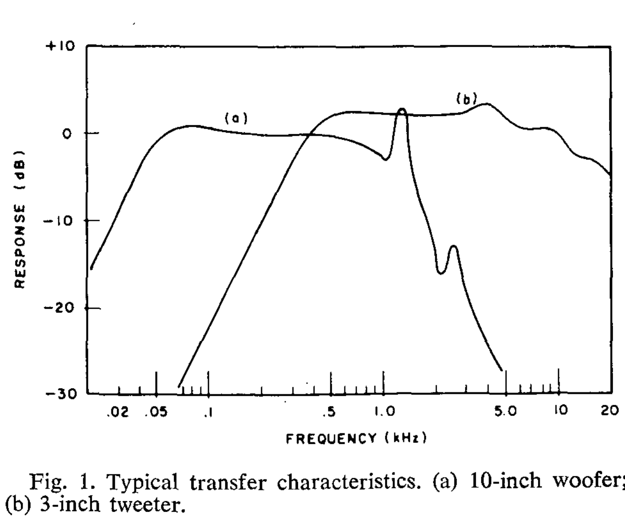

Fig. 1. Typical transfer characteristics. (a) 10-inch woofer; (b) 3-inch tweeter.

* Presented October 12, 1970, at the 39th Convention of the Audio Engineering Society, New York.
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The purpose of this paper is to study active and passive filter networks for use as loudspeaker crossover networks. We discuss the problem from a total system standpoint and point out the need for overlap in the responses of the drivers, the effect of driver impedance variations, the need to consider phase shift in the drivers and filter networks, etc. To keep the results from becoming too abstract, we use, as a typical example, the two-way direct radiator loudspeaker system which is a mainstay of the present audio equipment market. Such a loudspeaker, with a 10-inch woofer and a 3-inch tweeter in a 1.5-ft^3 closed box seems to have the blend of price, size, and performance which best satisfies the present market. By simple shifts of the frequency axes, the results we present can be applied to systems using different driver sizes.

DIRECT RADIATOR LOUDSPEAKER RESPONSE

Before we can consider the filter design aspect of the crossover problem, we must have a good idea of what the capabilities of the direct radiator loudspeaker are. Beranek gives an excellent general discussion of this problem [1, ch. 7]. Applying this theory to a 10-inch woofer with a correctly designed magnet [2] yields a driver with a transfer characteristic similar to that shown in Fig. 1, curve (a). The low frequency fall-off is caused by the failure of the system to maintain a constant acceleration characteristic below the resonant frequency. The 12-dB per octave fall-off above 1 kHz is caused by the radiation resistance reaching a constant value for this size cone [2]. The "spike" in the response is quite typical of the woofers we have measured and is caused by a standing wave along the cone as shown in [1, Fig. 7.9]. (Most woofers for closed-box systems have heavier (thicker) cones than the one referenced by Beranek and this accounts for a slight increase in the frequency of the spike.) In addition to these factors, the direct radiator loudspeaker becomes markedly more directive above 1 kHz, and the angle of the cone adds to this problem. Thus, the crossover network must inhibit woofer excitation above 1 kHz and direct this portion of the spectrum to the tweeter.

The tweeter obeys the same laws of nature as the woofer, but the lower mass, diameter, and compliance yield the curve shown in Fig. 1, curve (b). If the tweeter magnet is chosen properly, the efficiency will be equal to or slightly greater than the efficiency of the woofer because the mass and diameter decrease in such a way as to cause their individual effects to be canceled. This is desirable in a passive network system since the balance adjustment can then be made on the tweeter channel. The only parameter that does not scale directly is the frequency at which standing waves appear in the cone. Consequently, tweeters show considerable "roughness" in their high-frequency response and the only reasonable solution is to use a three-way system with a 1-inch driver for the upper end of the spectrum.

In addition to proper frequency division, the crossover network must protect the tweeter from the low-frequency end of the spectrum for two reasons. First, most of the power in the music spectrum [3] is concentrated below 1 kHz and the output of a 100-watt amplifier delivering the full music spectrum would be quite sufficient to destroy (by heat) the physically small and light-weight voice coil of the tweeter. Second, since the direct radiator tweeter is also operating in an acceleration mode, its displacement (for constant acoustic power output) must increase rapidly (12 db per octave) as frequency decreases. The tweeter cone does not have room to move more than a couple of millimeters; consequently, the crossover network must protect the tweeter from low tones to prevent the generation of gross harmonic distortion.

The driver considerations detailed above define the function of the crossover network and indicate that the role it plays is critical to proper overall loudspeaker system performance. From the standpoint of the drivers alone, the crossover network should have the highest possible slope in the stop band regions. We will see that this is more easily said than done when the total problem is considered.

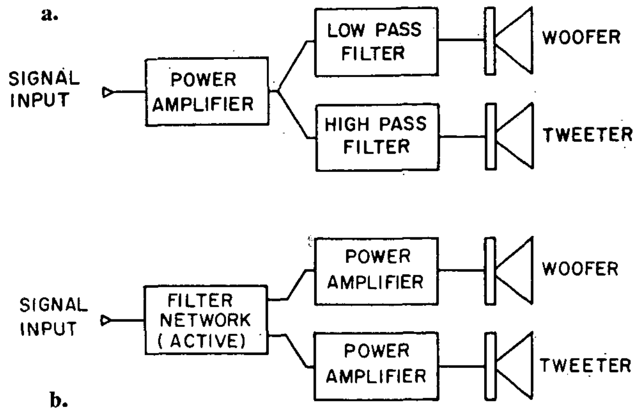


Fig. 2. **a.** Passive filter. **b.** Active filter.

PASSIVE AND ACTIVE FILTERS

Networks that achieve the frequency division desirable for crossover action in a multidriver loudspeaker system fall into two general categories. The type of network most commonly employed in commercially available systems is illustrated in Fig. 2**a**. In this arrangement, the composite signal to be reproduced is brought up to the level necessary to drive the transducers before any filtering is performed. The subsequent filtering, which is done at high level, is achieved by networks synthesized solely with passive (i.e., *R, L, C*) elements. Such filters are popular since a system employing passive filters requires only one power amplifier, and since the crossover network dissipates very little power and may be completely contained within the box that houses the various drivers of the loudspeaker system. This is usually considered to be a desirable state of affairs since most loudspeaker systems are presently marketed independently of power amplifiers.

The second general technique for solving the crossover problem is illustrated in Fig. 2**b**. Here the filtering necessary for frequency division is performed at low level. The various low-level signals are then routed through the separate power amplifiers that service the individual drivers of the loudspeaker system. The low-level filter used in the arrangement can be synthesized with either passive or active (with amplifiers) networks. Since the active network can be synthesized with only resistors, capacitors, and operational amplifiers [3], the current trend is to make electronic crossover networks with active filters. Although the cost of operational amplifiers at

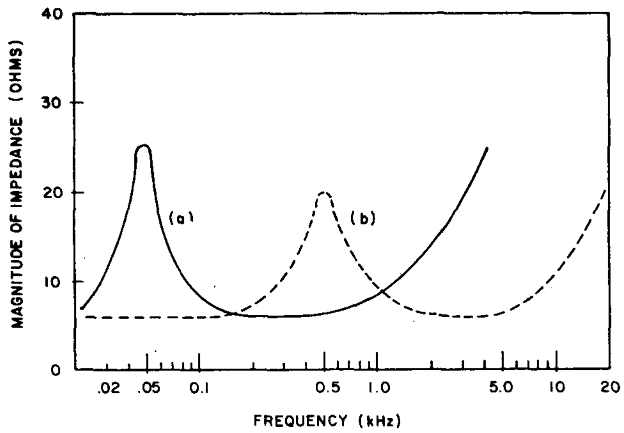


Fig. 3. Impedance characteristics of typical direct radiator driver loudspeakers. (a) 10-inch woofer; (b) 3-inch tweeter.

one time made synthesis of active crossover networks a strictly academic problem, recent advances in solid-state technology have increased the viability of active filters.

FILTER TERMINATIONS

It is most enlightening to study some of the problems inherent in the design of a passive crossover network. Most networks of this type are synthesized on the assumption that the network is terminated by a pure and constant resistance. The validity of this assumption, however, is questionable. Beranek [1] and Small [4] note that the impedance of the direct radiator loudspeaker is anything but a pure and constant resistance. As shown in curve (a) of Fig. 3, the impedance versus frequency characteristic of our typical 10-inch woofer has two significant deviations from constant resistance behavior. The low-frequency peak is caused by the mechanical resonance employed to achieve satisfactory low-frequency response in a direct radiator loudspeaker. The rise at the high-frequency end of the range is caused by the voice coil inductance. If the woofer is not designed for "long throw," this rise will occur above the frequency where other considerations have significantly decreased the woofer response. However, most small-box woofers are "long throw" to allow the motion required in the low bass region. The long-throw voice coil is usually double wound and some three centimeters long. This much wire near the soft iron of the pole piece will have a very significant inductance. Typically, the voice coil inductance of a long-throw woofer will give an automatic 6-dB per octave crossover at 600–800 Hz. In passive networks this inductance can be included as part of the inductor connected in series with the woofer if and only if the crossover frequency is lower than 600 Hz.

It is also interesting to note that the driver impedance of some 10 ohms causes passive filter elements (especially the capacitors) to be rather large. Intuitively we expect this since capactive reactances of tens of ohms can only be attained with tens or hundreds of microfarads at crossover frequencies less than 1 kHz.

The use of an active filter with separate buffer amplifiers to energize the various drivers alleviates most of these problems. With respect to the termination impedance of the filter, it is obvious that the buffer power amplifier isolates the driving point impedance of the loudspeaker from the output of the filter. The input impedance of the buffer amplifier can be made any desired value of pure and constant resistance and this eliminates the termination impedance problem for either active or passive realizations of the low-level crossover filters. Also, the very low Thevenin impedance of low-distortion power amplifiers is more suitable for exciting variable impedance driver units. *Thus, the buffer amplifier is better for both the filter termination and the loudspeaker driving source.*

The other problem caused by the loudspeaker as a termination impedance is the size of capacitors. The low-level filter can be synthesized for characteristic impedances of the order of kilohms, and this reduces capacitor size to the order of tenths of a microfarad. Passive filters which require inductors would be unwieldy as tens of henries would be required; however, the whole idea of active filter synthesis is to avoid the use of inductors, so this is not a significant problem. Thus, the inclusion of buffer power amplifiers allows the use of active filters synthesized with only resistors, capacitors, and operational amplifiers. The cost is much less than the cost of a good passive filter network at the 10-ohm level; furthermore, the availability of inexpensive 5-watt integrated-circuit power amplifiers alters the economic consideration regarding buffer amplifiers. If a high-slope crossover network is desired, it is actually less expensive to use operational amplifiers in active filters and integrated-circuit power amplifiers rather than a single power amplifier and a passive filter. Regarding marketing and compatibility problems, we will retreat to our ivory tower and offer no comments.

In the following sections we discuss several types of passive filters suitable for insertion between a single power amplifier and the driver loudspeakers. We will use the assumption of constant terminating impedance with the advice that a fair proficiency with computers is required to do otherwise. Then we summarize the use of active filter techniques with buffer power amplifiers for each of the driver loudspeakers.

BUTTERWORTH PASSIVE FILTERS

Various classes of filters may be employed in crossover design. A review of the approximation problem of modern network synthesis [5] gives a worthwhile comparison of modern filters. Bessel filters may be used since they have excellent phase and transient response characteristics. However, the frequency response change in the crossover region is too gradual for most loudspeakers. The Chebyshev equal-ripple filters achieve excellent frequency division with attendant wide fluctuations in input impedance. The best compromise between frequency response and input impedance seems to be the Butterworth characteristic. As pointed out by Ashley [7], the well-known 6- and 12-dB per octave constant resistance crossover networks are actually first- and second-order Butterworth filter networks.

The Butterworth low-pass characteristic

$$T[j(\omega/\omega_0)]T^*[j(\omega/\omega_0)] = \frac{1}{1+(\omega/\omega_0)^{2n}} \qquad (1)$$

where

$$\omega_0 = 2\pi f_c \qquad (2)$$

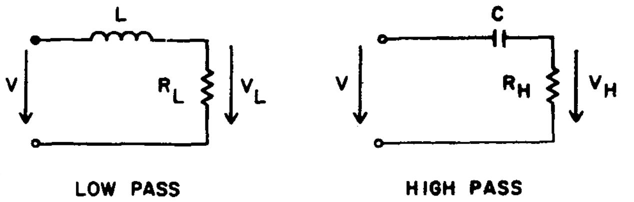


Fig. 4. First-order filter.

and f_c is the crossover frequency, is realized by implementing the low-pass transfer operator

$$T(p/\omega_0) = \frac{1}{B_n(p/\omega_0)} \tag{3}$$

where

$$p = d/dt = j\omega \tag{4}$$

$$s = p/\omega_0 \tag{5}$$

and $B_n(p/\omega_0)$ is a Butterworth polynomial of order n. These are given in Table I for reference.

Table I. Butterworth polynomials.

n	$B_n(s)$
1	$s+1$
2	$s^2+\sqrt{2}s+1$
3	s^3+2s^2+2s+1
4	$s^4+2.6131259s^3+3.4142136s^2+2.6131259s+1$
5	$s^5+3.2360680s^4+5.2360680s^3+5.2360680s^2+3.2360680s+1$

Consider now the first-order filter of Fig. 4. Clearly,

$$\frac{V_L}{V} = \frac{R_L/L}{s+R_L/L} \tag{6}$$

$$\frac{V_H}{V} = \frac{s}{s+1/R_HC}. \tag{7}$$

It is apparent that if

$$\omega_0 = \frac{R_L}{L} = \frac{1}{R_HC} \tag{8}$$

then

$$V_L+V_H = V \tag{9}$$

that is, if this first-order network is used, the sum of the outputs is a perfect replica of the input. This would seem to be a desirable property for a crossover network to have. Note that this first-order constant resistance filter is a Butterworth filter, with a stop-band slope of 6 dB per octave on both channels. Now the usual slope of a tone control circuit with the control in a maximum position is 6 dB per octave; thus, it is easy to observe how little the signals are actually attenuated in the stop-band region of this type of filter. The obvious consequence of this is that the two drivers must overlap in frequency response for about a 4-octave range; that is, the woofer must have nearly flat response through two octaves above crossover frequency and the tweeter must have nearly flat response for two octaves below crossover frequency. The curves we have presented for our typical 10-inch woofer and 3-inch tweeter do not meet this requirement, and we have found very few commercially available units where this requirement is met. The result is "roughness" in the crossover region which can be both measured and heard.

The obvious solution to this overlap problem is to increase the attenuation of the crossover filters in their stop-band region. That is to say, use a higher order Butterworth filter such as the second-order or 12-dB per octave constant resistance crossover network.

The schematic diagram of a second-order filter appears in Fig. 5. Here,

$$V_L/V = (\omega_{0L})^2/\{s^2+2\zeta_L\omega_{0L}s+(\omega_{0L})^2\} \tag{10}$$

where

$$(\omega_{0L})^2 = 1/L_LC_L$$

and

$$\zeta_L = (1/2R_L)\sqrt{L_L/C_L}. \tag{11}$$

Also,

$$V_H/V = s^2/\{s^2+2\zeta_H\omega_{0H}s+(\omega_{0H})^2\} \tag{12}$$

where

$$(\omega_{0H})^2 = 1/L_HC_H$$

$$\zeta_H = (1/2R_H)\sqrt{L_H/C_H}. \tag{13}$$

Now, if

$$\omega_{0L} = \omega_{0H} = \omega_0$$

$$\zeta_L = \zeta_H = \zeta = 1/\sqrt{2} \tag{14}$$

then this second-order crossover network is a second-order Butterworth filter. Note, in this case, that

$$(V_L+V_H)/V = (s^2+\omega_0^2)/(s^2+\sqrt{2}\omega_0s+\omega_0^2) \tag{15}$$

and observe that at the crossover frequency,

$$s = j\omega_0 \tag{16}$$

so that

$$(V_L+V_H)/V|_{s=j\omega_0} = 0. \tag{17}$$

This indicates a severe problem in the form of a "hole" in the frequency response at the crossover frequency. Ashley [6] demonstrated to the 13th Convention of the Audio Engineering Society that this "hole" can be heard.

One common solution to this problem that is currently employed by a number of loudspeaker manufacturers is to invert the polarity of, say, the woofer in the loudspeaker system. The information then received by the listener is actually

$$(V_H-V_L)/V = (s^2-\omega_0^2)/(s^2+\sqrt{2}\omega_0s+\omega_0^2). \tag{18}$$

This eliminates the hole at the crossover point as far as magnitude is concerned; however, a somewhat extraordinary phase characteristic is then produced.

For either the inverted or noninverted driver connec-

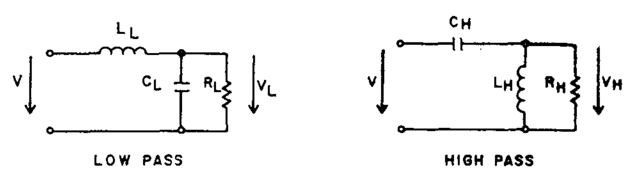
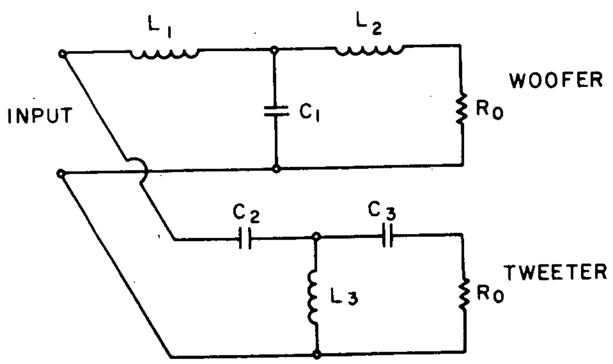


Fig. 5. Second-order filter.



DESIGN EQUATIONS

LOW PASS SECTION

$$L_1 = \frac{3R_0}{4\pi f_c}$$

$$L_2 = \frac{R_0}{4\pi f_c}$$

$$C_1 = \frac{2}{3\pi f_c R_0}$$

HIGH PASS SECTION

$$C_2 = \frac{1}{3\pi f_c R_0}$$

$$C_3 = \frac{1}{\pi f_c R_0}$$

$$L_3 = \frac{3R_0}{8\pi f_c}$$

Fig. 6. Third-order Butterworth filters as an 18-dB per octave constant-resistance frequency dividing network.

tion, the total power (without regard to cancellation because of phase) delivered by the loudspeakers is constant with frequency. Furthermore, the response of each filter output is down 3 dB at the crossover frequency and the slope is 12 dB per octave in the stop band. The requirement for more components is the usual reason for rejecting this kind of filter, but we feel that the actual decrease in sound quality (caused by the hole or extraordinary phase characteristic) is the more significant reason for not using this type of network.

Seeing the trouble that occurs in going from a first- to a second-order Butterworth filter might tend to make us ignore the third-order Butterworth in spite of its 18-dB per octave slope in the stop band. One author [7] was convinced that the hole at crossover frequency would be such a problem that the Butterworth filters above first-order would not be very useful for crossover networks. Then, Henne demonstrated with an analog computer [3]

Table II. Element values for third order Butterworth filters with 8 ohm drivers.

F_C (HZ)	L_1 (MH)	L_2 (MH)	C_1 (UF)	C_2 (UF)	C_3 (UF)	L_3 (MH)
100.00	19.10	6.37	265.26	132.63	397.89	9.55
125.89	15.17	5.06	210.70	105.35	316.05	7.59
158.49	12.05	4.02	167.37	83.68	251.05	6.03
199.53	9.57	3.19	132.94	66.47	199.42	4.79
251.19	7.60	2.53	105.60	52.80	158.40	3.80
316.23	6.04	2.01	83.88	41.94	125.82	3.02
398.11	4.80	1.60	66.63	33.31	99.94	2.40
501.19	3.81	1.27	52.93	26.46	79.39	1.91
630.96	3.03	1.01	42.04	21.02	63.06	1.51
794.33	2.40	.80	33.39	16.70	50.09	1.20
1000.00	1.91	.64	26.53	13.26	39.79	.95
1258.93	1.52	.51	21.07	10.54	31.61	.76
1584.89	1.21	.40	16.74	8.37	25.10	.60
1995.26	.96	.32	13.29	6.65	19.94	.48
2511.89	.76	.25	10.56	5.28	15.84	.38
3162.28	.60	.20	8.39	4.19	12.58	.30
3981.07	.48	.16	6.66	3.33	9.99	.24
5011.87	.38	.13	5.29	2.65	7.94	.19
6309.57	.30	.10	4.20	2.10	6.31	.15
7943.28	.24	.08	3.34	1.67	5.01	.12
10000.00	.19	.06	2.65	1.33	3.98	.10

that the third-order Butterworth filter crossover network has flat voltage and power frequency response with a gradual change in phase across the band. As demonstrated at the 38th Convention of the Audio Engineering Society, this change in phase across the band cannot be heard. This means that the third-order Butterworth filter must receive serious consideration as a high-level crossover network.

Straightforward application of the methods of modern network synthesis [5] yields the third-order Butterworth crossover network of Fig. 6. This filter will have 3-dB attenuation at the crossover frequency (as do all Butterworth filters) and a slope of 18 dB per octave in the stop band. Listening to the individual channels when this filter is used, it becomes evident that a much higher attenuation exists in the stop band than when a first-order filter is used; indeed, this filter is not a bad approximation to the "stone wall" effect previously described.

We note in passing that a fourth-order Butterworth crossover network will have the same problem as a second-order filter and is not to be recommended. However, the fifth-order filter does have the same properties as the third-order filter, except for a total phase shift change of 720° instead of 360°. Weinberg [5] gives all the information needed to synthesize all of the Butterworth filters, and his tables will quickly yield the fifth-order filter. Since the third-order filter seems to be of considerable importance, we have used a computer to generate Table II giving the element values for 8-ohm drivers.

QUASI-SECOND-ORDER PASSIVE CROSSOVER NETWORKS

In the previous section, we described the frequency response problem with second-order constant-resistance filters that led Ashley [6] to suggest a buffered crossover network which forced the phasor voltages applied to the drivers to add up to the applied voltage. The use of buffer amplifiers makes possible a true 12 dB/octave slope in the high-pass filter. (See the second order curves of Fig. 14). This basic idea has been generalized for passive filters by Small's development of what he has termed a "constant voltage crossover network." [4] Working independently on a commercially available loudspeaker system, Kaminsky generalized the series connected first-order Butterworth filter by relaxing the constant input impedance constraint and obtained the quasi-second-order filter shown in Fig. 7. Here

$$\frac{V_L}{V} = \frac{s+(R_L+R_H)\omega_0/2R_L\zeta}{R_H C(s^2+2\zeta\omega_0 s+\omega_0^2)} \tag{19}$$

$$\frac{V_H}{V} = \frac{s(s+2\zeta R_H\omega_0/[R_L+R_H])}{s^2+2\zeta\omega_0 s+\omega_0^2} \tag{20}$$

where

$$\omega_0^2 = 1/LC$$

$$\zeta = (R_L+R_H)/(2R_L R_H)\sqrt{L/C}. \tag{21}$$

Observe that

$$V_L+V_H = V \tag{22}$$

as, indeed, it must if Kirchhoff is to be satisfied. If, as is usually the case,

$$R_L = R_H = R \tag{23}$$

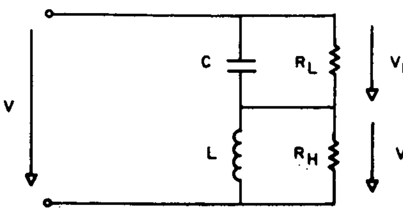


Fig. 7. A simple quasi-second order passive crossover network.

(19) and (20) reduce to

$$\frac{V_L}{V} = \frac{s+\omega_0/\zeta}{RC(s^2+2\zeta\omega_0 s+\omega_0{}^2)}. \tag{24}$$

$$\frac{V_H}{V} = \frac{s(s+\zeta\omega_0)}{s^2+2\zeta\omega_0 s+\omega_0{}^2}. \tag{25}$$

If $\zeta = 1$, then this configuration specifies a first-order filter. However, suppose that $\zeta = 0.5$. Then a straight-line Bode plot reveals the approximate behavior of the filter to be as follows. The low-frequency channel cuts off at 12 dB per octave at ω_0 and 6 dB per octave above $2\omega_0$; the high-frequency channel cuts off at 12 dB per octave at ω_0 and 6 dB per octave below $0.5\omega_0$. Hence, the appellation of quasi-second-order seems appropriate for this filter. This is illustrated in Fig. 8.

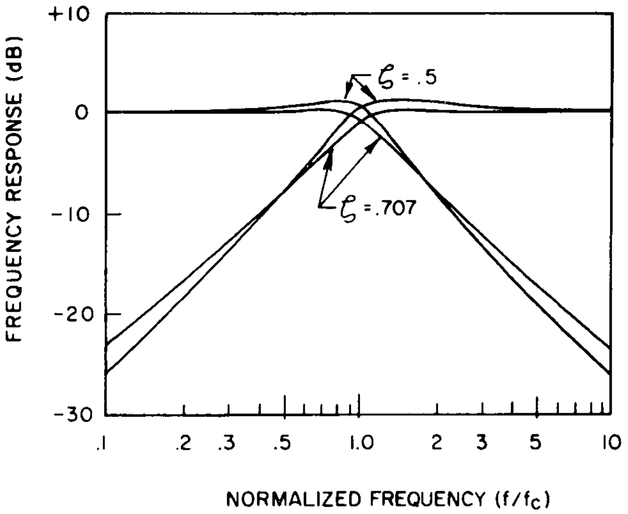


Fig. 8. Frequency response of the quasi-second order filters.

The class of filters exemplified in this section (such filters are possible for any order) have desirable characteristics that do not stop at the lack of phase error. One of these is that the quasi-second-order filter has half the components of a conventional second-order filter. The other is that component tolerances are not as important as in conventional crossover networks, since a slight error in the crossover point affects both channels in a complementary manner.

Computer-generated element values for this crossover network with 8-ohm terminations are listed in Table III.

Table III. Element values for quasi-second-order filters with 8 ohm drivers.

	ZETA = 1/SQRT(2)		ZETA = 1/2	
F (HZ) C	L (MH)	C (UF)	L (MH)	C (UF)
100.00	9.00	281.35	6.37	397.89
125.89	7.15	223.48	5.06	316.05
158.49	5.68	177.52	4.02	251.05
199.53	4.51	141.01	3.19	199.42
251.19	3.58	112.01	2.53	158.40
316.23	2.85	88.97	2.01	125.82
398.11	2.26	70.67	1.60	99.94
501.19	1.80	56.14	1.27	79.39
630.96	1.43	44.59	1.01	63.06
794.33	1.13	35.42	.80	50.09
1000.00	.90	28.13	.64	39.79
1258.93	.72	22.35	.51	31.61
1584.89	.57	17.75	.40	25.10
1995.26	.45	14.10	.32	19.94
2511.89	.36	11.20	.25	15.84
3162.28	.28	8.90	.20	12.58
3981.07	.23	7.07	.16	9.99
5011.87	.18	5.61	.13	7.94
6309.57	.14	4.46	.10	6.31
7943.28	.11	3.54	.08	5.01
10000.00	.09	2.81	.06	3.98

ACTIVE FILTERS FOR CROSSOVER NETWORKS

In the preceding sections we have demonstrated that an active filter network followed by buffer amplifiers is a better solution to the crossover problem, from the standpoint of flexibility and economics, than is a system with passive high-level filters. In this section we survey some of the better techniques for synthesizing active filters with high-gain operational amplifiers.

First-order filters can be realized by simple *R-C* networks, but the slope of 6 dB per octave in the stop bands is not high enough to justify the system complexity. A straightforward realization of second-order high- and low-pass filters will have exactly the same hole at the crossover frequency that plagued the second-order Butterworth passive network. The third-order conventional Butterworth high- and low-pass filter networks do have flat frequency response and can be synthesized with only two operational amplifiers. This attractive filter is shown in Fig. 9. Application of the tables of values for Butterworth filters, as given in Foster [8], yields the typical component values shown in Table IV. (This filter, with a crossover frequency of 318 Hz, was demonstrated at the 38th Convention of the Audio Engineering Society.) The values for the high-pass filter are based on a characteristic impedance of 20 kΩ.

The real advantage of the active-filter approach is that the constant-voltage crossovers are simple to synthesize. Following Small [4], we consider both symmetrical and asymmetrical crossover characteristics. We restrict our

Table IV. Element values for operational amplifier filters.

F HZ	C0 (UF)	C1 (UF)	C2 (UF)	C3 (UF)	C5 (UF
100.00	.07958	.37797	.41237	.05173	.15915
125.89	.06321	.30023	.32756	.04109	.12642
158.49	.05021	.23848	.26019	.03264	.10042
199.53	.03988	.18943	.20667	.02593	.07977
251.19	.03168	.15047	.16417	.02059	.06336
316.23	.02516	.11952	.13040	.01636	.05033
398.11	.01999	.09494	.10358	.01299	.03998
501.19	.01588	.07541	.08228	.01032	.03176
630.96	.01261	.05990	.06536	.00820	.02522
794.33	.01002	.04758	.05191	.00651	.02004
1000.00	.00796	.03780	.04124	.00517	.01592
1258.93	.00632	.03002	.03276	.00411	.01264
1584.89	.00502	.02385	.02602	.00326	.01004
1995.26	.00399	.01894	.02067	.00259	.00798
2511.89	.00317	.01505	.01642	.00206	.00634
3162.28	.00252	.01195	.01304	.00164	.00503
3981.07	.00200	.00949	.01036	.00130	.00400
5011.87	.00159	.00754	.00823	.00103	.00318
6309.57	.00126	.00599	.00654	.00082	.00252
7943.28	.00100	.00476	.00519	.00065	.00200
10000.00	.00080	.00378	.00412	.00052	.00159

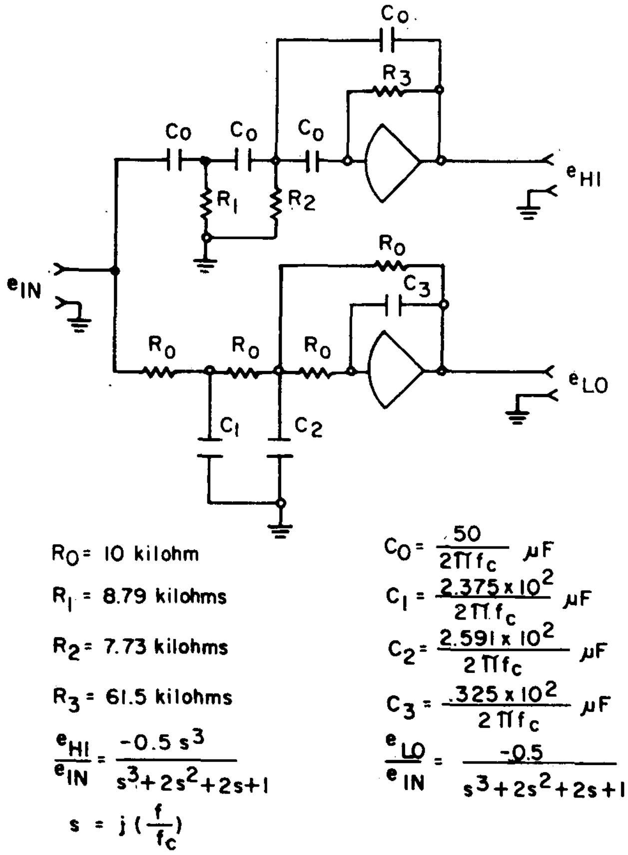


Fig. 9. Realization of the third-order Butterworth electronic crossover network with Rauch filters.

methods to those employing high-gain operational amplifiers because of the availability of inexpensive, high-performance, integrated-circuit devices.

The simplest approach to either symmetrical or asymmetrical electronic crossover synthesis is to use the method suggested by Ashley [6], [7] which requires only one filter network. The second-order symmetrical filter is shown in

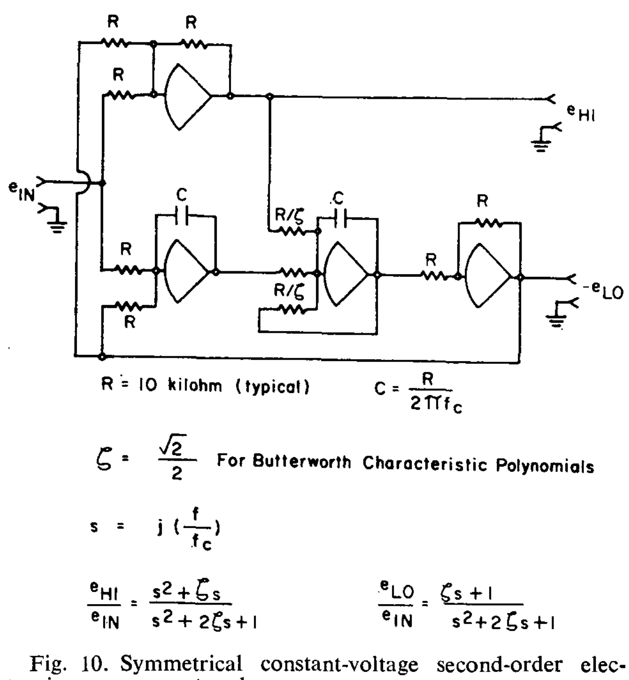


Fig. 10. Symmetrical constant-voltage second-order electronic crossover network.

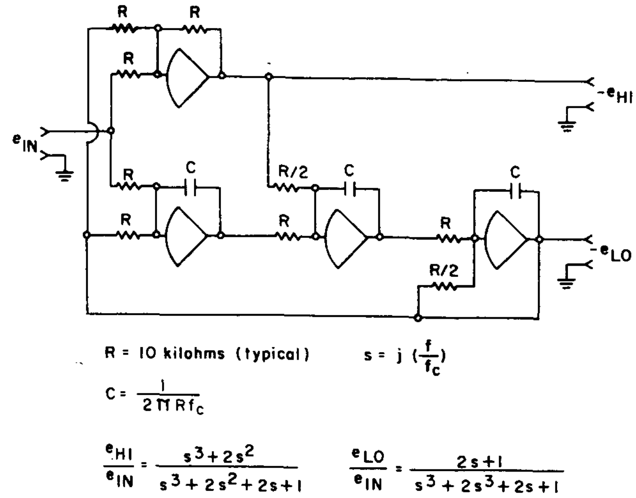


Fig. 11. Symmetrical constant-voltage electronic crossover network with third-order Butterworth characteristic function.

Fig. 10. In this case, we have chosen to synthesize a low-pass filter and then derive (by subtraction) the high-frequency output. This requires one less operational amplifier than synthesizing the high-pass filter and deriving the low-frequency output. Observe that the damping coefficient ζ can be modified by changing only two resistors, and that the crossover frequency f_c is controlled by two capacitors. (The capacitor size for 10-kΩ resistors is given in column C5 of Table IV.) This network is the electronic analog of the quasi-second-order passive crossover network and will have the frequency response of Fig. 8.

Applying this same approach to a filter with a third-order characteristic function yields the symmetrical network of Fig. 11. Here we have combined the function of the summing operational amplifier in such a way that this network requires only four operational amplifiers. Since this is the same number required for the second-order network, there is considerable motivation to use this network and obtain the 12-dB per octave slope in both pass

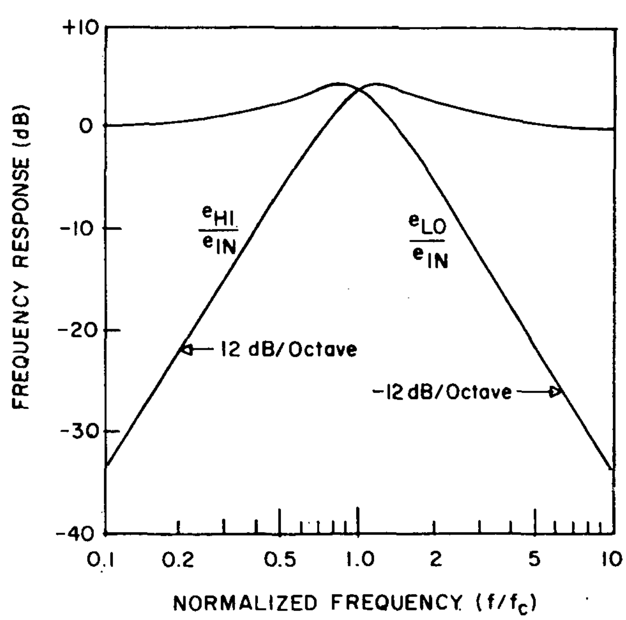


Fig. 12. Frequency response of modified third-order Butterworth electronic crossover network.

bands as shown in Fig. 12. Again, capacitor sizes are given in the C5 column of Table IV.

It is possible to synthesize higher order filters of this type with the cost measured in additional operational amplifiers. Since the third-order filters offer a significant improvement in performance as compared to presently available passive filter networks, we will leave the rather obvious details to those who can demonstrate a justifying need for such systems.

The synthesis of asymmetrical constant-voltage networks can be accomplished, for up to third-order characteristics functions, as shown in Fig. 13. Here the basic filter section is a high-pass active network and the low-frequency channel is derived by subtraction. The resultant high-pass characteristic is desirable because the frequency response shown in Fig. 14 is better matched to the capabilities of both buffer amplifiers and driver units. The third-order Butterworth high-pass filter in Fig. 13 can be constructed using the capacitor values of Table IV. This simple network is a good solution to the crossover problem if the woofer driver has extended response in the high-frequency range.

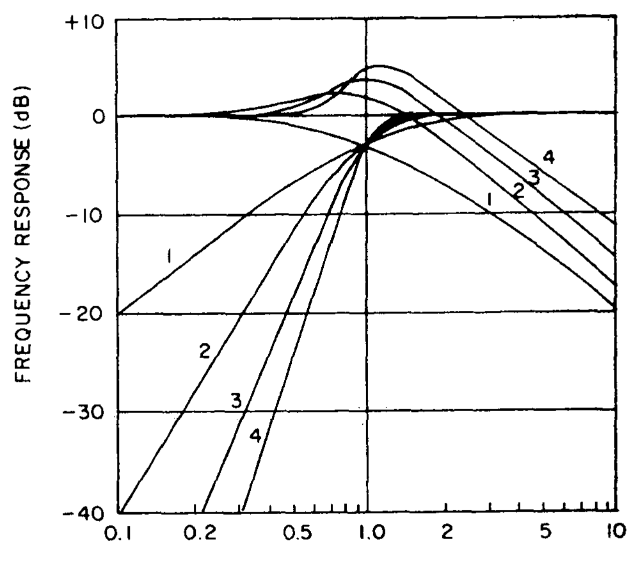
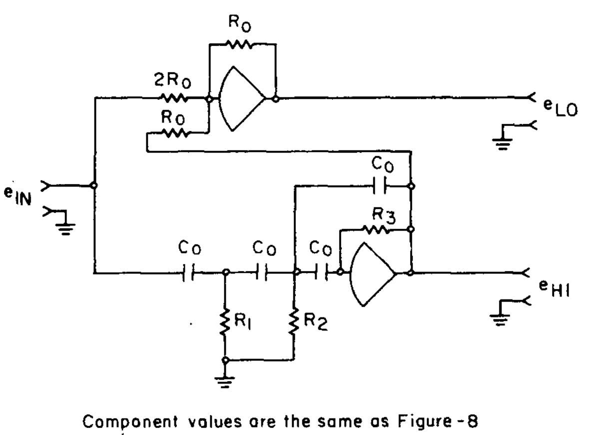


Fig. 14. Frequency response of asymmetrical crossover networks with Butterworth characteristic functions.



$$\frac{e_{HI}}{e_{IN}} = \frac{-0.5\,s^3}{s^3+2s^2+2s+1} \qquad \frac{e_{LO}}{e_{IN}} = \frac{-0.5\,(2s^2+2s+1)}{s^3+2s^2+2s+1}$$

$$s = j\left(\frac{f}{f_c}\right)$$

Fig. 13. Asymmetrical constant-voltage active filter crossover network with third-order Butterworth characteristic function.

CONCLUDING REMARKS

The consideration of all aspects of the crossover problem for direct radiator loudspeaker systems points to several optimum designs for various size and power capabilities. The two-way loudspeaker constrained to a 2-ft^3 box should have a 10-inch woofer and a 3-inch tweeter with a $\zeta = 0.5$ quasi-second-order passive crossover network designed for a crossover frequency of about 800 Hz. Decreasing the box size would call for a smaller woofer and an increase in the crossover frequency. Substitution of a passive third-order Butterworth filter for the quasi-second-order filter would result in a slight improvement in performance near the crossover frequency, but it is doubtful if this improvement is worth the added cost for this kind of loudspeaker system.

The next significant level of system performance improvement requires a larger cabinet and a three-way system. Using a 5-ft^3 box, a 12-inch woofer, 5-inch midrange, and 1-inch tweeter leads to a most interesting crossover network design. Small [4] gives the network needed for three-way constant-voltage crossover and the crossover frequencies should be set at 500 and 2500 Hz. (Kaminsky has designed a similar network for a commercially available three-way system.)

Further increase in system performance will require a still larger cabinet and more woofer cone area. A 10-ft^3 box with two 12-inch woofers is an elaborate enough starting point to justify the active filter approach. Proper selection of a low-mass large-magnet 8-inch mid-range driver will allow a 5-watt buffer amplifier to match a 30-watt buffer amplifier driving the woofers. The low-frequency electronic crossover at 316 Hz should be the symmetrical third-order network of Fig. 10. The crossover to a 2-inch tweeter at 1585 Hz can be done with a $\zeta = 0.5$ quasi-second-order network. Such a loudspeaker system would be nearly the ultimate which could be achieved with direct radiator drivers.

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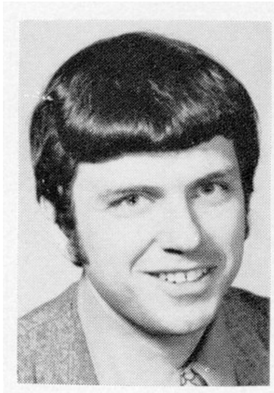
THE AUTHOR



Allan L. Kaminsky was born in Brooklyn, New York in 1941. He received the B.S. degree in electrical engineering from Newark College of Engineering in 1966, and M.S. and Ph.D. degrees from Columbia University in 1967 and 1970 respectively.

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Note: Dr. Ashley's biography appeared in the October, 1970 Journal.