all about CROSSOVER networks

by HOWARD M. TREMAINE

author of The Audio Cyclopedia

Helps you get the most from hi-fi systems. Discusses design and theory of crossover networks, plus how to build and test them, determining crossover network frequencies, and other important factors.

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PREFACE

Present-day high-fidelity loudspeaker systems encompass a wide frequency range, and most of them utilize two or more speakers along with a frequency-controlling (crossover) network. Since the crossover network controls the bandwidth of the signals to each speaker, it is one of the important components of the system. Often an otherwise good speaker system does not perform as it should, simply because the crossover network is either inadequate or improperly designed.

This book was prepared because of a lack of collected information on crossover networks. In it you will find information on their basic principles, design, and construction. The book is written for the service technician seeking knowledge to help him maintain his customers' hi-fi equipment, and for the do-it-yourself audiophile or hobbyist who finds enjoyment in designing and assembling his own hi-fi system. Charts and tables have been included to eliminate the necessity for computing component values, along with simple instructions for constructing, testing, and phasing a speaker system.

The subject of crossover networks has too long been buried in obscurity. If my small contribution brings this little-known but all-important subject into the limelight it so richly deserves, the purpose of this book shall have been fulfilled.

H. M. Tremaine

September, 1960

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SECTION 1

General Network Theory

1.1 General

High-fidelity sound reproduction requires a loudspeaker system with a frequency range of at least 40 to 10,000 cps. For extreme high-fidelity reproduction and frequency-modulation reception, this range must be extended to cover a bandwidth between 30 and 15,000 cps. To obtain such a wide bandwidth, it is customary to use two or more separate loudspeakers in a single enclosure. Each unit is limited to a given frequency range, since it is impractical to reproduce such a wide range of frequencies with a loudspeaker employing a single diaphragm.

It is also impractical to connect both a high-frequency and low-frequency speaker directly to the output of an amplifier. Such a connection will result in the full frequency range of the amplifier being applied to both speakers simultaneously. High frequencies fed to the low-frequency unit will be lost because of the inability of the latter to reproduce such frequencies. Likewise, the low frequencies are lost when fed to a high-frequency unit. In addition, the diaphragm of the high frequency unit could easily be damaged if the low frequencies drive it beyond its normal length of travel.

If the frequency range applied to each unit is limited, and only those frequencies which it can most efficiently reproduce are applied, higher efficiency can be achieved from the entire system. This will result in a wider frequency range, smoother over-all response, and lower distortion, particularly of the intermodulation type.

A two-way speaker system consists generally of a low-frequency and a separate high-frequency unit. A frequency-controlling network, termed a *crossover network*, is employed to limit the frequency response of each speaker to its most efficient range. This is accomplished in a smooth, efficient manner, and as a result, the two speakers appear to reproduce as a single unit.

A crossover network for a two-way speaker system consists of two sections—a low- and a high-pass filter. The low-pass section limits the high-frequency response of the low-frequency unit, and the high-pass section limits the low-frequency response of the high-frequency unit.

A three-way speaker system is composed of low-, midrange, and high-frequency units. The crossover network consists of three filter sections—a low-pass, a bandpass, and a high-pass. The low- and high-pass sections function as for the two-way system. The bandpass section limits the frequency response of the midrange unit, permitting it to extend only into a small portion of the low and high frequencies. This results in a smooth over-all transition between the three units. Thus, the reproduction creates the illusion that the sound is coming from a single speaker. A typical commercial crossover network for a two-way system appears in Fig. 1-1.

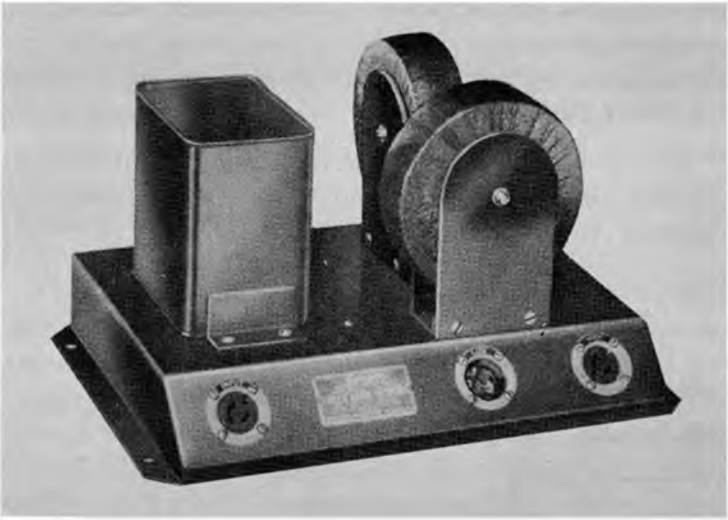


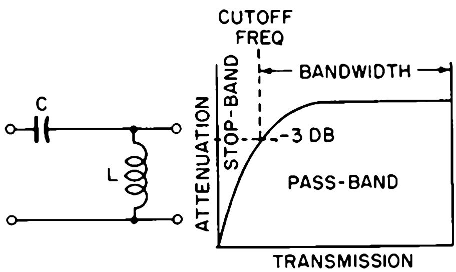
Fig. 1-1. A typical commercial crossover network. (Courtesy of Jensen Manufacturing Company.)

At the outset, it should be understood the sole purpose of a crossover network is to limit the frequency range of a given speaker and to provide a smooth electrical transition from one speaker to the other. It cannot correct deficiencies in the frequency response of the speakers nor the enclosure in which they are operated. The network, if properly designed and operated in conjunction with good-quality speakers, and if mounted in a properly designed enclosure, will result in a smooth response from the lowest to the highest frequency covered by the system.

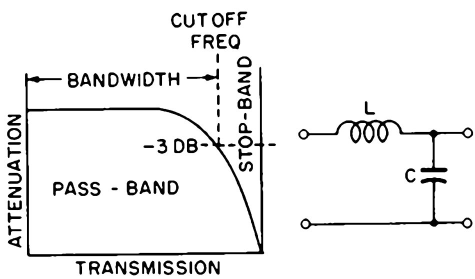
To achieve optimum response from any speaker system, the crossover network must reflect the proper load impedance to the output of the amplifier and to the speakers. Because the network is connected between the output of the power amplifier and speakers, it must not induce an appreciable amount of *insertion loss* (loss due to power dissipated within the network by its elements). Insertion loss reduces the available output power of the amplifier driving the speaker system.

1.2 Filter Terminology

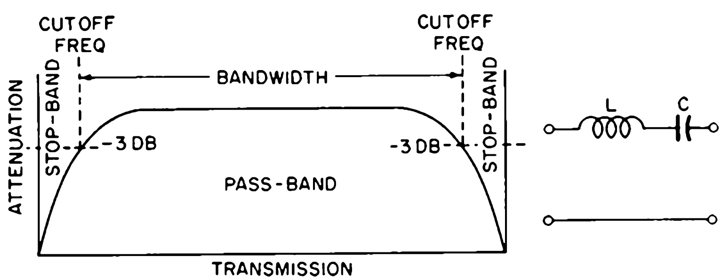
To help you understand the terminology used throughout this text, three basic filters, their configurations, and response curves are shown in Fig. 1-2.



(A) High-pass filter.



(B) Low-pass filter.



(C) Band-pass filter.

Fig. 1-2. Three basic filter configurations and their response curves.

The high-pass filter in Fig. 1-2A is a network of capacitive and inductive elements which attenuates all frequencies *below* a predetermined frequency, but passes all those above the cutoff frequency.

The low-pass filter in Fig. 1-2B is a network of reactive elements which attenuates all frequencies *above* a predetermined frequency, but passes all those *below* the cutoff frequency.

The bandpass filter in Fig. 1-2C is a network which passes only a predetermined band of frequencies. All frequencies above and below the cutoff frequencies are attenuated.

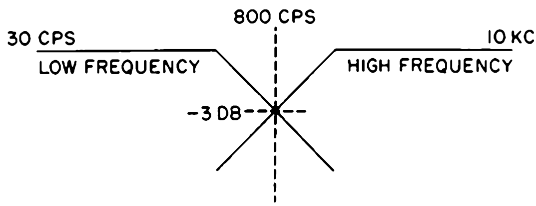
The basic difference between a low- and a high-pass filter is the manner in which the circuit elements are connected. Those for a high-pass filter are connected inversely to the circuit elements of the low-pass filter, whereas those for a bandpass filter are connected in series.

1.3 Crossover Frequency

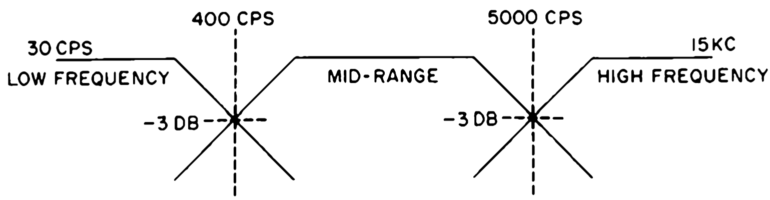
The selection of crossover frequencies for a network is dictated by the frequency response of the speakers to be employed. As a rule, a low-frequency unit designed for use in a two-way system is limited to frequencies ranging from 30 to about 2,000 cps, after which it falls off in response quite rapidly. High-frequency units are generally designed to cover a frequency band from 400 cps to some higher frequency. The crossover frequency may be somewhere between 400 and 1,000 cps.

In a three-way system, an intermediate speaker is added to cover the midrange frequencies from about 400 to 6,000 cps. The high-frequency unit is designed to operate from about 4,000 cps to 15,000 cps or higher. Crossover frequencies could be 400 and 5,000 cps, for example. These factors, of the utmost importance in the design of the network, must be fully taken into consideration when the crossover frequencies are selected. The frequency range of a particular speaker is determined from the manufacturer's data sheet for the unit under consideration. Any good 12- to 15-inch speaker can be used for the low-frequency unit; however, it is more satisfactory to use a unit designed especially for low-frequency operation.

Typical frequency-response characteristics for two- and three-way networks are shown in Fig. 1-3. Fig. 1-3A shows



(A) Two-way crossover network.



(B) Three-way crossover network.

Fig. 1-3. Typical frequency-response characteristics of crossover networks.

the frequency response that might be used with a two-way system. Note that the low- and high-frequency units cross over at a frequency 3 db down from the over-all response level (the flat portion of the frequency spectrum). In a three-way system (Fig. 1-3B), the frequency spectrum is divided into three sections, and each speaker again crosses over at a frequency 3 db down from the over-all level.

The rate of attenuation (fall-off) at the crossover point may be 6, 12, or 18 db per octave, depending on the requirements of the system. An octave is the interval between two frequencies when one frequency is double that of the other, or, in other words, has a ratio of 2:1. In theory, the loss of the network at the crossover frequency is 3 db. However, in practical networks the loss may approach 4 db, depending on the efficiency of the network components. Losses greater than 4 db should be avoided. However, do not confuse the 6-, 12-, and 18-db rate of attenuation with the 3-db loss at the crossover frequency.

At the crossover frequency, the voltage and the power are divided equally between the high- and low-frequency units (assuming they are of the same impedance).

The ultimate frequency response of any multiple speaker system is a combination of the frequency response of the network and the *acoustical output* of the speakers in the system.

Fig. 1-4 shows typical frequency design characteristics for crossover networks, with cutoff rates of 6, 12 and 18 db per octave. The point where the curves cross over is termed the crossover frequency. At this frequency the characteristics of the filter sections are such that the frequency response drops off above or below the crossover frequency at a prescribed rate. If 1.0 on the graph represents the crossover frequency (f), then 0.5 would represent one octave *below* the crossover frequency, and 0.25, two octaves below. Similarly, 2.0 would represent one octave *above*, and 4.0, two octaves above, the crossover frequency.

The curves in Fig. 1-4 are for an *ideal* crossover filter in which there are no losses. However, in a practical filter some losses occur because of the dissipative factors in the filter elements. The first octave for a 12-db-per-octave filter will fall off only about 10 to 11 db, and thereafter, 12 db. The 6-db per-octave filters fall off at a rate of 5 db for the first octave, and the 18-db per-octave ones fall off at about 17 db. This small variation in the cut off rate is not too important and may be ignored. The exception is the *m*-derived filter to be discussed later.

The crossover frequency must start becoming effective before the response of the speaker falls off and the move-

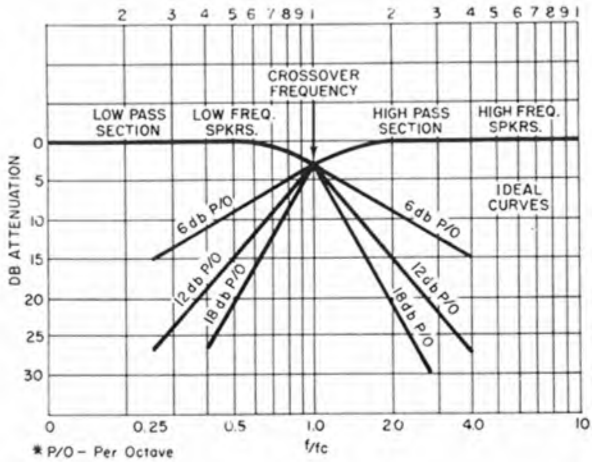


Fig. 1-4. Typical frequency characteristic for ideal 6-, 12-, and 18-db-per-octave crossover networks.

ment of the diaphragm becomes nonlinear. Low-frequency speakers, especially designed for multiple-speaker systems, seldom have much response above 1,000 cps. The frequency response of the high-frequency unit must be restricted to those frequencies where the wavelengths are such that the excursion of the diaphragm will not exceed the diaphragm displacement, as recommended by the manufacturer.

Six-db-per-octave networks do not provide a rapid enough cutoff rate; therefore, damage to the high-frequency units can result unless the network cuts off at a frequency high enough to protect the unit. The low-frequency unit must be capable of handling at least one octave *above* the crossover frequency, and the high-frequency unit, one octave *below* the crossover frequency, at the full power output of the driving amplifier. The use of the 12-db-per-octave rate of cutoff will overcome this difficulty.

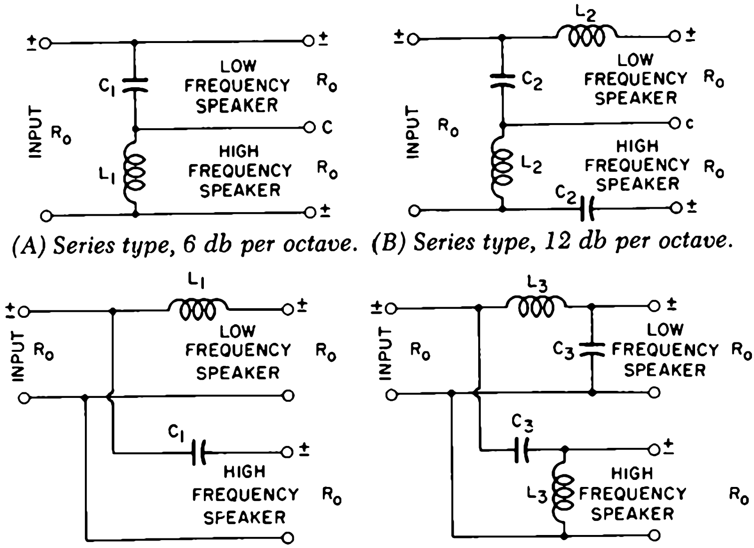
The cutoff rate of the filter sections can be controlled by the designer. Simple networks employ a 6-db-per-octave rate, whereas the more elaborate ones employ the 12- or 18-db-per-octave rate. The 12-db rate of cutoff is the most common.

1.4 Configuration

The selection of an electrical configuration for a network is not critical—either a parallel or series type can be used. However, the parallel type does offer a slightly better characteristic in the attenuation and transmission bands. Series type configurations are used with two-way systems only.

Several circuit configurations are available to the network designer—the constant k (Fig. 1-5), and the m-derived (Fig. 1-6). Most commercial networks employ the constant-k, constant-resistance type, using the parallel configuration in Fig. 1-5C or D. Theoretically, the constant-k, constant-resistance network will reflect a constant-resistance back to the output of the power amplifier when the output sections are terminated in a *resistive* load. But since the speakers do *not* reflect a resistive load, the amplifier output does not see a constant resistance. This disadvantage is compensated for somewhat by the use of negative feedback in the amplifier.

In a constant-resistance network, the frequency response of the two filter sections is complementary. The sum of the power delivered to the output section is constant for a constant-input voltage to the input terminals of the network. When the output sections are terminated in a resistive load, the input impedance presented by the network to the amplifier output is constant throughout the entire frequency range. The frequency response of the filter sections in the



(A) Series type, 6 db per octave. *(B) Series type, 12 db per octave.*

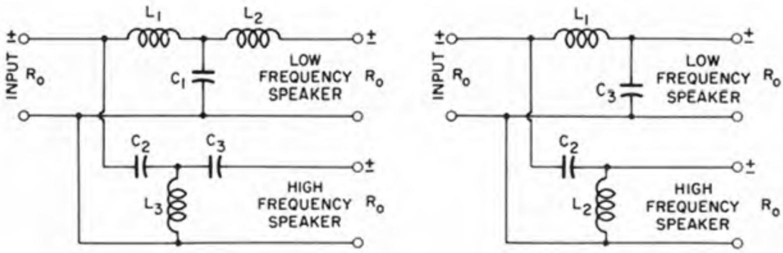
(C) Parallel type, 6 db per octave. *(D) Parallel type, 12 db per octave.*

$C_1 = \frac{1}{\omega_c R_o}$ FARAD	$L_1 = \frac{R_o}{\omega_c}$ HENRY	$\omega_c = 2\pi f_c$
$C_2 = \sqrt{2}\, C_1$ FARAD	$L_2 = \frac{L_1}{\sqrt{2}}$ HENRY	R_o = SPEAKER IMPEDANCE
$C_3 = \frac{C_1}{\sqrt{2}}$ FARAD	$L_3 = \sqrt{2}\, L_1$ HENRY	f_c = CROSSOVER FREQ

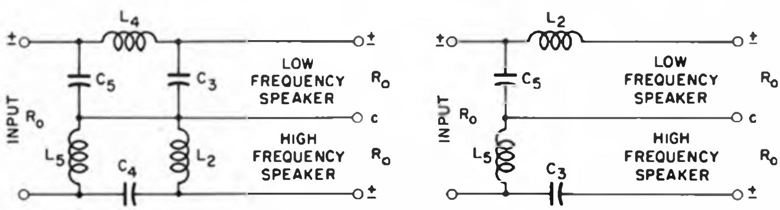
Fig. 1-5. Constant-*k*, constant-resistance crossover networks and their design equations.

passband is uniform, with a constant phase difference at the outputs of the high- and low-frequency sections.

Constant-*k* networks are limited to a maximum cutoff rate of 12 db per octave. The *m*-derived crossover networks can also be used to provide a 12-db or greater rate of cutoff. An additional advantage of the *m*-derived filter is that the impedance and attenuation characteristics can be more closely controlled by the designer. The term *m* is a numerical constant between zero and 1.0 which is used in circuit-element equations, as shown in Fig. 1-6. The *m*-de-



(A) Parallel type, 18 db per octave. (B) Parallel type, 12 db per octave.



(C) Series type, 18 db per octave. (D) Series type, 12 db per octave.

$C_1 = \frac{2}{\omega_c R_o}$ FARAD	$L_1 = (1+m)\frac{R_o}{\omega_c}$ HENRY	
$C_2 = \left(\frac{1}{1+m}\right)\frac{1}{\omega_c R_o}$ FARAD	$L_2 = \frac{R_o}{\omega_c}$ HENRY	$\omega_c = 2\pi f_c$
$C_3 = \frac{1}{\omega_c R_o}$ FARAD	$L_3 = \frac{R_o}{2\omega_c}$ HENRY	R_o = SPEAKER IMPEDANCE
$C_4 = \frac{1}{2\omega_c R_o}$ FARAD	$L_4 = \frac{2R_o}{\omega_c}$ HENRY	f_c = CROSSOVER FREQ.
$C_5 = (1+m)\frac{1}{\omega_c R_o}$ FARAD	$L_5 = \left(\frac{1}{1+m}\right)\frac{R_o}{\omega_c}$ HENRY	$m = 0.6$

Fig. 1-6. Conventional *m*-derived crossover networks and their design equations.

rived filters can be designed to match about 85 per cent of the frequency bands covered by the filter. In audio work, *m* is generally made to equal 0.6, and this is the value selected for the design data in this text. In special cases, where the speaker impedance does not match the amplifier output impedance, the network may be designed to operate between unequal impedances, as described in Section 2.3. For this type of network design, the equations given in the diagram must be employed.

1.5 Network Impedance

For most speaker installations, particularly those in the home, the impedance of the network will generally be 4, 8, or 16 ohms. The network, which may be either a series or a parallel configuration, is mounted at the speaker enclosure. The design impedance of the network and speakers is selected to reflect a proper impedance match between the amplifier output, the network, and the speakers.

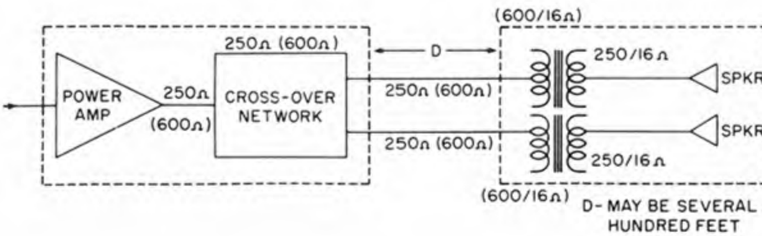


Fig. 1-7. 250-ohm crossover network with 250-ohm transmission line.

In motion-picture theaters and similar commercial installations, the amplifier driving the speaker system is often separated by several hundred feet. In this instance, a 250- or 600-ohm transmission line is employed to feed the amplifier output signal to a crossover network installed at the speaker end. The transmission line generally consists of rather large-gauge wire enclosed in metal conduit.

Two methods of feeding a remote speaker system are employed in large installations. In the first method (Fig. 1-7), a 250- or 600-ohm crossover network is placed at the amplifier, and the output sections of the network are fed to the remote speaker system over a transmission line. At the speaker end, transformers provide an impedance match between the network and the low impedance of the speakers. In the second method (Fig. 1-8), a 600-ohm crossover network is placed at the speaker end and fed from the amplifier over a 600-ohm line. Again, transformers are used to effect an impedance match between the network and speakers. Using an impedance of 250 to 600 ohms for the transmission line permits the signal to be transmitted at a

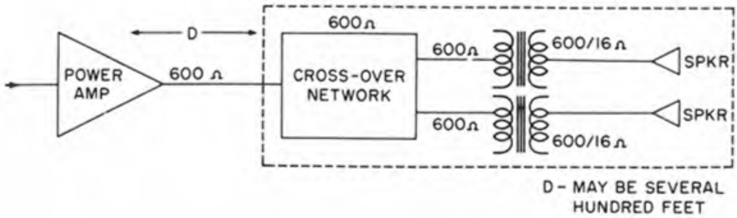


Fig. 1-8. 600-ohm crossover network with 600-ohm transmission line.

high voltage and low current. This has a definite advantage where large amounts of power must be transmitted over a line several hundred feet in length. The recommended maximum lengths for a given wire size, using output impedances of 4, 8, or 16 ohms, are shown in Table 1-1. Data for lines of 100, 250, and 600 ohms are given in Table 1-2.

Table 1-1. Maximum length run and wire size for lines with an impedance of 4, 8, and 16 ohms.

Wire Size	4 Ohms	8 Ohms	16 Ohms
	Length in Feet	Length in Feet	Length in Feet
14	125	250	450
16	57	150	300
18	50	100	200
20	25	50	100

The longer the transmission line, the greater the attenuation of the higher frequencies will be because of the perimeters of the line. High-frequency attenuation, rela-

Table 1-2. Maximum length run and wire size for lines with an impedance of 100, 250, and 600 ohms.

Wire Size	100 Ohms	250 Ohms	600 Ohms
	Length in Feet	Length in Feet	Length in Feet
14	1,000	2,500	5,000
16	750	1,500	3,000
18	400	1,000	2,000
20	250	750	1,500

tive to 1,000 cps for lines of a given size and length, is tabulated in Table 1-3. For the home installation, the distance between the amplifier and speaker system rarely exceeds fifty feet and attenuation can generally be ignored. However, in some instances the amplifier may tend to become unstable because of the capacitance of the line. This will cause the amplifier to oscillate and thereby distort the program material. If the transmission line is over fifty feet in length, it should be connected to a water-pipe ground. Amplifiers employing negative-feedback circuitry are generally grounded to the amplifier chassis. In this instance, the ground is connected at the amplifier chassis.

Table 1-3. Maximum recommended length of a line for a given high-frequency loss.

Wire Size	Maximum Length in Feet (Pair)			
	3 Kc	5 Kc	7.5 Kc	10 Kc
10	5,000	3,800	3,000	2,700
12	4,000	3,100	2,500	2,000
14	3,000	2,400	2,000	1,700
16	2,500	1,900	1,500	1,350

1.6 Network Elements

The selection of network elements (inductors and capacitors) is quite important because they affect the frequency characteristics and insertion loss of the network. The coils must have a low DC resistance, and the internal losses of the capacitors must also be low because the insertion loss of the network is created by the series DC resistance of the coils and by the shunt reactance of the capacitors.

The coils are wound using an air core, and a rather large-gauge wire is employed. Coils using an iron core are not recommended; they introduce intermodulation distortion into the system due to saturation of the iron. As a rule, the inductance required in a network ranges from 0.30 to 25 millihenrys. Such coils can be easily wound onto a simple coil form, using a scrambled or layer winding.

Whenever possible, paper- or oil-dielectric capacitors should be employed. However, at the higher circuit impedances and at the lower frequencies, the value of capacitance becomes rather large and the units rather costly. For large capacitance values, motor starting capacitors make an excellent capacitor bank and can be easily obtained.

Until recently, electrolytic capacitors were not recommended for crossover-network use because they are designed to operate in circuits carrying direct current. DC maintains their capacitance, polarization, and other characteristics, whereas only AC voltage appears in a crossover network. Recent research on this subject* has proved that the present-day electrolytic capacitors are feasible in a crossover network, provided they are shunted with a small paper- or oil-dielectric capacitor to reduce their internal impedance at higher frequencies.

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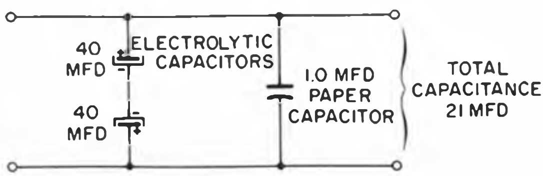
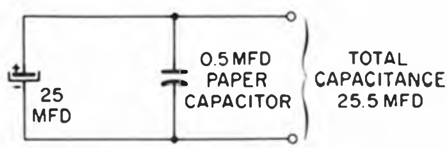
* Cohen, Abraham B. and Paul D., "Hi-Fi Crossover Networks," *Radio and Television News*, April 1959, page 45.

Electrolytic capacitors can be used in a network by connecting two, with the same capacitance and voltage ratings, back-to-back as shown in Fig. 1-9. Connecting like polarities together, or back-to-back, reduces the effects of polarization and permits an electrolytic capacitor to be used in an AC circuit. Electrolytic capacitors of this nature are termed nonpolarized. Using the connection shown in Fig.



(A) Connected back-to-back in parallel with oil- or paper-dielectric capacitor.



(B) Single polarized electrolytic capacitor shunted with an oil- or paper-dielectric capacitor.

Fig. 1-9. Method of connecting electrolytic capacitors when used in a crossover network.

1-9A, if two 40-mfd capacitors are connected in series, the total capacitance will be 20 mfd. The individual units can be connected negative-to-negative or positive-to-positive with like results.

The use of electrolytic capacitors will increase the insertion loss of the network slightly, and will also reduce the cutoff rate. However, being small, these losses are not too important. When electrolytic capacitors are used in the high-pass filter section to feed the high-frequency speaker, they must be bypassed by a small paper- or oil-dielectric

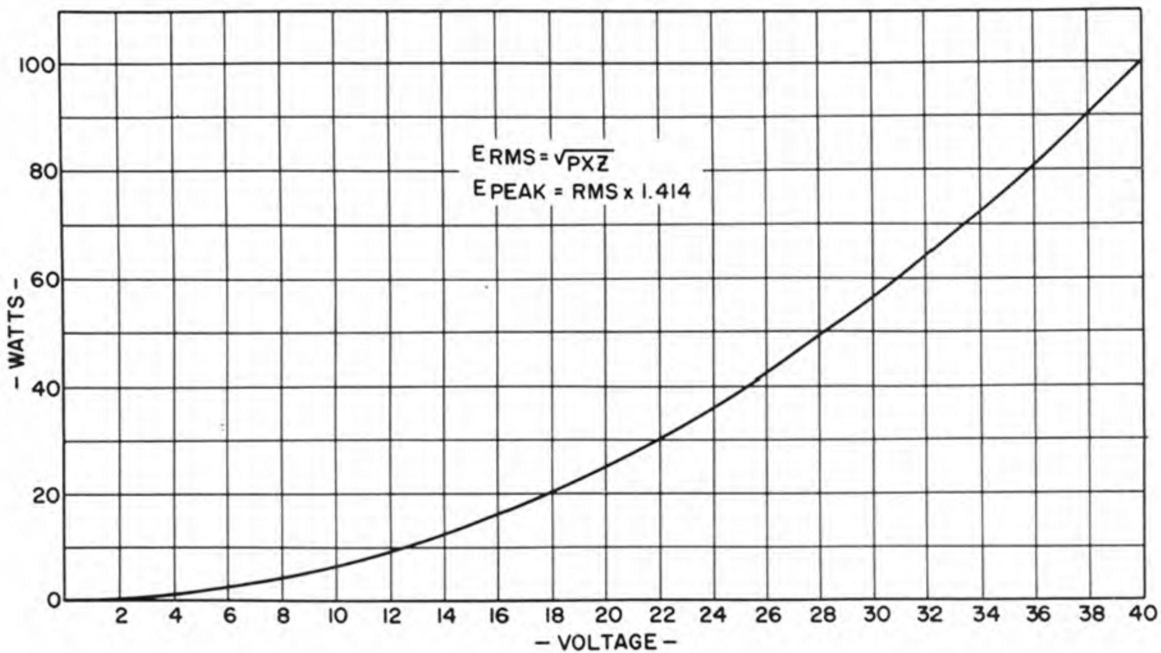


Fig. 1-10. Rms voltage *versus* power in a 16-ohm network.

capacitor connected in parallel with the electrolytic bank (Fig. 1-9A). This will offset the effect of the rising impedance of electrolytic capacitors at higher frequencies. This additional capacitance is included in the total circuit capacitance. Electrolytic capacitors can be expected to vary from their rated value 20 to 30 per cent. This makes it essential that the capacitance be measured with a capacitance bridge. Values should be selected ±3% if the crossover point is to be close to the designed frequency. Normal polarized electrolytic capacitors also can be used in crossover networks (Fig. 1-9B). However, the nonpolarized type appears to be more satisfactory.

Regardless of the capacitor used, it must have an AC voltage rating equal to or greater than the highest voltage expected in the network. As an example, if the amplifier driving the network has a power output of 40 watts, the rms voltage at an impedance of 16 ohms will be around 25.3 volts when the amplifier is delivering its full power output. To convert rms to peak voltage, multiply the rms value by 1.414. Thus, for a 40-watt amplifier the peak voltage will be 35.77 volts. For a paper- or oil-dielectric capacitor, a rating of 50 volts is ample. If electrolytic capacitors are employed, they should have a rating of at least 150 volts. To guide the designer in determining the voltage developed in a network for a given power output, Fig. 1-10 is a graph showing the rms voltage developed by amplifiers of various output powers working into a 16-ohm load. To determine the voltage in the network, enter the graph at the left, which represents the power output in watts of the driving amplifier. Follow the horizontal line to the point where it intersects the curved line. Then read the voltage by following the vertical line downward to the value indicated at the bottom of the graph.

SECTION 2

Network Design

*2.1 Constant-*K *Network Design*

The question often arises as to which network offers the best advantage—a 6- or a 12-db rate of cutoff? If cost is a factor, the 6-db-per-octave is more economical because only two circuit elements are required. However, speaker systems employing a 6-db-per-octave network apparently do not have the definition the same system has with a 12-db-per-octave rate of cutoff. Also, an improperly designed 6-db-per-octave network can damage the high-frequency speaker by permitting the low frequencies to pass on to the high-frequency unit.

Another factor is that, when the circuit impedance is 4 or 8 ohms, the values of capacitance required increases quite rapidly, whereas the inductance decreases. Because the cost of inductors is small, compared with the cost of capacitors, the most economical design impedance appears to be 16 ohms. When a 6-db-per-octave network is to be employed, the crossover frequency for the high-frequency speaker must be higher than for a 12-db-per-octave cutoff rate, if the physical displacement of the diaphragm in the high-frequency speaker is not to exceed the manufacturer's specifications. If this precaution is not observed, the diaphragm may be damaged. This is particularly true for the midrange and high-frequency units in a three-way system. For the low-frequency unit, this factor is not too important.

Assume a two-way, 16-ohm impedance network is to be designed to feed a low- and a high-frequency unit, using a crossover frequency of 800 cps and a 12-db-per-octave cutoff rate. Referring to the configuration for a 12-db-per-octave parallel network in Fig. 1-5D, note that four circuit elements are required—two coils and two capacitors. Also note that both coils and both capacitors bear the same symbols (L3 and C3). Therefore, they have the same inductance and capacitance values. Using the equation in the diagram and solving for L3 requires that we first solve for a similar network configuration, using a 6-db-per-octave rate of cutoff as in Fig. 1-5C. Thus, inductance L1 in Fig. 1-5C is solved:

$$\begin{aligned} L1 &= \frac{R_0}{\omega_c} \\ &= \frac{16}{2\pi f_c} \\ &= \frac{16}{6.28 \times 800} \\ &= 0.00318 \text{ henrys.} \end{aligned}$$

Solving for L3 (12-db p/o):

$$\begin{aligned} L3 &= \sqrt{2}L1 \\ &= 1.414 \times 0.00318 \\ &= 0.00449 \text{ henrys} \\ &= 4.49 \text{ millihenrys} \end{aligned}$$

Solving for C1 (Fig. 1-5C):

$$C1 = \frac{1}{\omega_c R_o}$$

$$= \frac{1}{2\pi f_c R_o}$$

$$= \frac{1}{6.28 \times 800 \times 16}$$

$$= 0.0000124 \text{ farads}$$

$$= 12.4 \text{ microfarads}$$

Solving for C3 (12 – db p/o):

$$C3 = \frac{C1}{\sqrt{2}}$$

$$= \frac{0.0000124}{1.414}$$

$$= 0.00000876 \text{ farads}$$

$$= 8.76 \text{ microfarads}$$

If the final values of the circuit elements are held to within ±3% of the computed values, they will be quite satisfactory. The coils can be easily wound to within this tolerance. It is really of little consequence whether an 800-cps network crosses over at 776 or 824 cps, since it would have little or no effect on the reproduction. The exact values of capacitance are obtained by paralleling several individual units. Circuit-element values for the series-type configuration networks are solved in a similar manner.

To simplify the design of constant-*k*, constant-resistance networks, the circuit-element values for circuit impedances of 4, 8, and 16 ohms have been tabulated in Tables 2-1, 2-2, and 2-3 respectively. Although in some instances the values have been carried out to three places, they may be rounded off for practical purposes.

Table 2-1. Values for constant-*k*, constant-resistance networks for a 4-ohm impedance.

f_c	250	300	350	400	450	500	600	800	1000	2000	3000	4000	5000	6000
C1	159.3	132.7	113.5	99.5	88.5	79.6	66.4	49.7	39.8	19.9	13.27	9.95	7.96	6.64
C2	225.2	187.6	161.6	140.7	125.1	112.6	93.8	70.4	56.2	28.12	18.76	14.07	11.26	9.38
C3 (A,B,C)	112.6	93.8	80.0	70.4	62.5	56.3	46.9	35.2	28.1	14.05	9.38	7.04	5.63	4.69
L1	2.55	2.12	1.82	1.59	1.42	1.27	1.06	0.80	0.64	0.32	0.21	0.16	0.13	0.1
L2	1.80	1.50	1.29	1.12	1.00	0.90	0.75	0.56	0.45	0.22	0.15	0.11	0.10	0.07
L3 (A,B,C)	3.6	3.0	2.57	2.25	2.00	1.80	1.50	1.12	0.90	0.45	0.30	0.23	0.20	0.15

C=Microfarads L=Millihenrys R_o=4 Ohms f_c=Crossover Frequency, cps

Table 2.2. Values for constant-*k*, constant-resistance networks for an 8-ohm impedance.

f_c	250	300	350	400	450	500	600	800	1000	2000	3000	4000	5000	6000
C1	79.5	66.4	55.75	49.8	44.3	39.8	33.2	24.8	19.9	9.95	6.64	4.98	3.98	3.32
C2	112.6	93.8	80.8	70.4	62.5	56.3	46.9	35.2	28.1	14.06	19.38	7.04	5.63	4.69
C3 (A,B,C)	56.3	46.9	40.2	35.2	31.3	28.1	23.5	17.6	14.1	7.03	4.69	3.52	2.81	2.35
L1	5.1	4.25	3.64	3.18	2.83	2.54	2.12	1.59	1.27	0.64	0.43	0.32	0.25	0.21
L2	3.6	3.0	2.57	2.25	2.00	1.80	1.50	1.13	0.90	0.45	0.30	0.23	0.18	0.15
L3 (A,B,C)	7.2	6.0	5.17	4.50	4.00	3.60	2.99	2.26	1.79	0.90	0.60	0.45	0.36	0.299

C=Microfarads L=Millihenrys R_o=8 Ohms f_c=Crossover Frequency, cps

Table 2-3. Values for constant-*k*, constant-resistance networks for a 16-ohm impedance.

f_c	250	300	350	400	450	500	600	800	1000	2000	3000	4000	5000	6000
C1	39.8	33.2	28.4	24.8	22.1	19.9	16.6	12.4	9.9	4.96	3.32	2.48	1.99	1.66
C2	56.5	46.8	40.0	35.2	31.2	28.2	23.4	17.6	14.1	7.03	4.68	3.52	2.82	2.34
C3 (A,B,C)	28.1	23.4	20.0	17.6	15.6	14.1	11.7	8.80	7.03	3.51	2.34	1.76	1.41	1.17
L1	10.2	8.5	7.28	6.4	5.7	5.1	4.2	3.2	2.54	1.27	0.85	0.64	0.51	0.42
L2	7.2	6.0	5.15	4.5	4.0	3.6	3.0	2.3	1.79	0.90	0.60	0.45	0.36	0.30
L3 (A,B,C)	14.4	12.0	10.3	9.0	8.0	7.2	6.0	4.5	3.58	1.79	1.20	0.90	0.72	0.60

C = Microfarads L = Millihenrys R_o = 16 Ohms f_c = Crossover Frequency, cps

2.2 m-*Derived Network Design*

Neither the constant-*k* series nor parallel type of network attenuates at 12 db per octave, either above or below the crossover frequency, but does approach this rate after the first octave. If, for reasons of design, it is desirable that the cutoff rate be 12 db for the first octave, this may be obtained by the use of an *m*-derived network, either the parallel- or series-type configuration, as shown in Figs. 1-6B and D.

Note that for the *m*-derived network the values of the capacitors and inductors are not the same for each section, as they are in the constant-*k* type. To simplify the design, component values may be selected from Tables 2-4, 2-5, and 2-6. Values for three-way networks may also be selected from these same tables, as described in Section 2.5.

As a rule, 18-db-per-octave networks are seldom used. For those desiring to experiment with this rate of cutoff, the circuit configurations are given in Figs. 1-6A and C. Note that six circuit elements, all of different values, are required. The circuit-element values for such networks have been tabulated in Tables 2-4, 2-5, and 2-6.

2.3 *Networks for Unequal Impedances*

At times the speakers on hand do not match the output impedance of the power amplifier. If a network is designed for a given impedance and the speaker does not match it, considerable power will be lost. Also, the quality of reproduction may be affected by the fact that the proper load impedance is not reflected to the network and amplifier. A simple but effective method of matching speakers of unequal impedance through a network and back to the amplifier is shown in Fig. 2-1A. The output transformer has two taps—in this instance, 8 and 16 ohms. The circuit is in reality a parallel-type network using a 12-db-per-octave rate of cutoff.

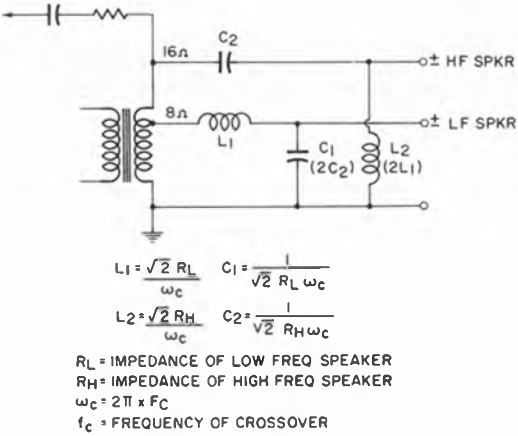


Fig. 2-1A. Method of matching speakers of unequal impedances.

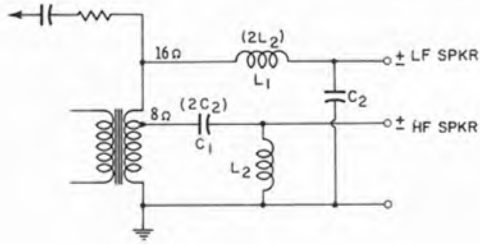


Fig. 2-1B. Circuit when higher impedance speaker is used for low-frequency work.

In cases where the higher impedance speaker is used for low-frequency work refer to Fig. 2-1B. Should a low-frequency speaker of 16 ohms impedance be used along with a high-frequency speaker of 8 ohms impedance the ratio or proportion of the component values would be:

$$L_1 = \frac{\sqrt{2}\,R_L}{W_c} \qquad \text{and} \qquad L_2 = \frac{\sqrt{2}\,R_H}{W_c}$$

In proportion,

$$L_1 = \frac{16\sqrt{2}}{W_c} \qquad \text{and} \qquad L_2 = \frac{8\sqrt{2}}{W_c}$$

L_1 and L_2 are in the ratio or proportion of 16 to 8, or 2 to 1, respectively. Therefore, $L_1 = 2L_2$.

$$C_1 = \frac{1}{\sqrt{2}\, R_H\, W_c} \qquad \text{and} \qquad C_2 = \frac{1}{\sqrt{2}\, R_L\, W_c}$$

In proportion,

$$C_1 = \frac{1}{8\sqrt{2}\, W_c} \qquad \text{and} \qquad C_2 = \frac{1}{16\sqrt{2}\, W_c}$$

C_1 and C_2 are in the ratio or proportion of 1/8 to 1/16, or 2 to 1, respectively. Therefore, $C_1 = 2C_2$.

An alternate method of using speakers of unequal impedance is shown in Fig. 2-2. Matching is accomplished

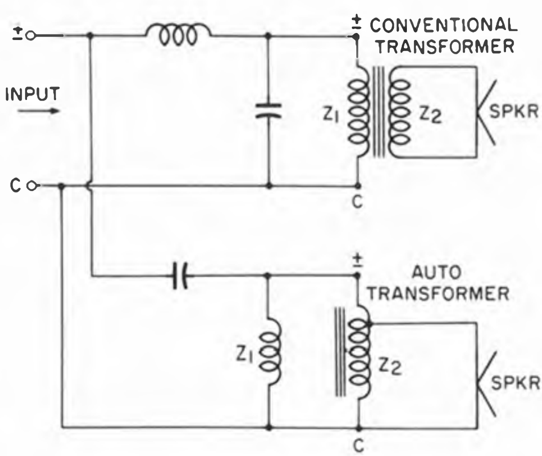


Fig. 2-2. An alternate method of matching speakers of unequal impedances.

Table 2-4. Values for m-derived crossover networks for a 4-ohm impedance.

f_c	250	300	350	400	450	500	600	800	1000	2000	3000	4000	5000	6000
C1	318.5	265.4	245.0	199.1	176.9	159.3	132.7	99.5	79.6	39.8	26.5	19.9	15.9	13.27
C2 (A)	99.5	82.9	71.1	62.2	55.3	49.8	41.5	31.1	24.8	12.4	8.29	6.22	4.98	4.15
C3 (A)	159.2	132.7	113.7	99.5	88.5	79.6	66.4	49.8	39.8	19.9	13.3	9.95	7.96	6.64
C4	79.6	66.3	56.9	49.8	44.2	39.8	33.2	24.9	19.9	10.0	6.63	4.98	3.98	3.32
C5	254.8	212.5	182.	159.2	141.5	127.4	106.2	79.6	63.7	31.8	21.25	15.92	12.74	10.62
L1 (A)	4.08	3.40	2.92	2.55	2.26	2.04	1.70	1.27	1.02	0.51	0.34	0.26	0.20	0.17
L2 (A)	2.55	2.12	1.82	1.59	1.42	1.27	1.06	0.80	0.64	0.32	0.21	0.16	0.12	0.10
L3	1.27	1.06	0.91	0.80	0.71	0.64	0.53	0.40	0.32	0.16	0.11	0.08	0.06	0.053
L4	5.10	4.25	3.64	3.18	2.83	2.55	2.12	1.59	1.27	0.64	0.43	0.32	0.26	0.212
L5	1.59	1.33	1.18	1.00	0.88	0.80	0.66	0.50	0.40	0.20	0.13	0.10	0.08	0.066

C = Microfarads m = 0.60 L = Millihenrys R_o = 4 Ohms f_c = Crossover Frequency, cps

Table 2-5. Values for *m*-derived crossover networks for an 8-ohm impedance.

f_c	250	300	350	400	450	500	600	800	1000	2000	3000	4000	5000	6000
C1	159.2	132.7	124.7	99.6	88.5	79.6	66.4	49.8	39.8	19.9	13.27	9.96	7.96	6.64
C2 (A)	49.8	41.5	35.5	31.1	27.6	24.9	20.7	15.6	12.4	6.2	4.15	3.11	2.49	2.07
C3 (A)	79.6	66.4	56.9	49.8	44.2	39.8	33.2	24.9	19.9	9.9	6.64	4.98	3.98	3.32
C4	39.8	33.2	28.4	24.9	22.1	19.9	16.6	12.4	9.9	5.0	3.32	2.49	1.99	1.66
C5	127.4	106.2	91.0	79.6	70.8	63.7	53.1	39.8	31.8	15.9	10.62	7.96	6.37	5.31
L1 (A)	8.15	6.79	5.82	5.10	4.53	4.08	3.40	2.54	2.04	1.02	0.68	0.51	0.41	0.340
L2 (A)	5.10	4.25	3.64	3.18	2.83	2.54	2.12	1.59	1.28	0.64	0.43	0.32	0.25	0.212
L3	2.54	2.12	1.81	1.59	1.42	1.28	1.06	0.80	0.64	0.32	0.21	0.16	0.12	0.1
L4	10.19	8.50	7.28	6.37	5.66	5.10	4.25	3.18	2.54	1.27	0.85	0.64	0.51	0.425
L5	3.18	2.66	2.27	1.99	1.77	1.59	1.33	0.99	0.80	0.40	0.27	0.20	0.16	0.133

C = Microfarads   m = 0.60   L = Millihenrys R_o = 8 Ohms f_c = Crossover Frequency, cps

Table 2-6. Values for m-derived crossover networks for a 16-ohm impedance.

f_c	250	300	350	400	450	500	600	800	1000	2000	3000	4000	5000	6000
C1	79.6	66.4	62.4	49.9	44.2	39.8	33.2	24.9	19.9	9.95	6.64	4.49	3.98	3.32
C2 (A)	24.9	20.7	17.7	15.6	13.8	12.4	10.4	7.8	6.2	3.10	2.07	1.56	1.24	1.04
C3 (A)	39.8	33.2	28.4	24.9	22.1	19.9	16.6	12.4	9.9	4.98	3.32	2.49	1.99	1.66
C4	19.9	16.6	14.2	12.4	11.1	10.0	8.4	6.2	5.0	2.49	1.66	1.24	1.0	0.84
C5	63.6	53.1	45.5	39.8	35.4	31.8	26.5	19.9	15.9	7.96	5.31	3.98	3.18	2.65
L1 (A)	16.3	13.6	11.65	10.2	9.1	8.2	6.8	5.1	4.1	2.04	1.36	1.02	0.82	0.68
L2 (A)	10.2	8.5	7.28	6.4	5.7	5.1	4.2	3.2	2.6	1.27	0.85	0.64	0.51	0.42
L3	5.1	4.2	3.63	3.2	2.8	2.5	2.1	1.6	1.3	0.64	0.42	0.32	0.25	0.21
L4	20.4	17.0	14.5	12.8	11.3	10.2	8.4	6.4	5.1	2.54	1.70	1.28	1.02	0.84
L5	63.7	53.1	45.4	39.8	35.4	31.8	26.6	19.8	15.9	7.95	5.31	3.98	3.18	2.68

C = Microfarads m = 0.60 L = Millihenrys R_o = 16 Ohms f_c = Crossover Frequency, cps

through impedance matching transformers, either the autotransformer or the conventional two-winding type. However, this is an expensive manner of accomplishing the objective, since the transformers must be capable of carrying the full power of the amplifier and still have a uniform response over the frequency range required by the particular unit. Also, by introducing an additional insertion loss, transformers reduce the available power to the speakers.

2.4 Impedance Conversion

Although the data given in the tabulations in Tables 2-1 through 2-6 are for the most common impedances, they can be converted to other impedance values by the use of two simple equations:

$$L_x = \left(\frac{Z_1}{R_0}\right) L \qquad\qquad C_x = \frac{C}{\left(\frac{Z_1}{R_0}\right)}$$

where L_x is the new inductance, L is the original inductance, R_0 is the impedance given in the tables, Z_1 is the new impedance, C_x is the new capacitance, and C is the original capacitance. The filter data given in the tables can be converted to frequencies other than those indicated, by the simple expedient of changing the values of inductance and capacitance inversely with frequency. The circuit-element values are multiplied or divided by the ratio of the known frequency to the desired frequency.

2.5 Three-Way System Networks

A three-way speaker crossover network differs only in the addition of the midrange (bandpass filter) circuit elements. Fig. 2-3 shows the configuration for a three-way, constant-*k* network using a 6-db-per-octave rate of cutoff. Basically, the configuration in Fig. 2-3 is the same as the one in Fig.

1-5C, except for the addition of the midrange circuit elements C1A and L1A.

Referring to Fig. 2-3 and its equations, the circuit-element values for C1A and L1A are calculated in the same

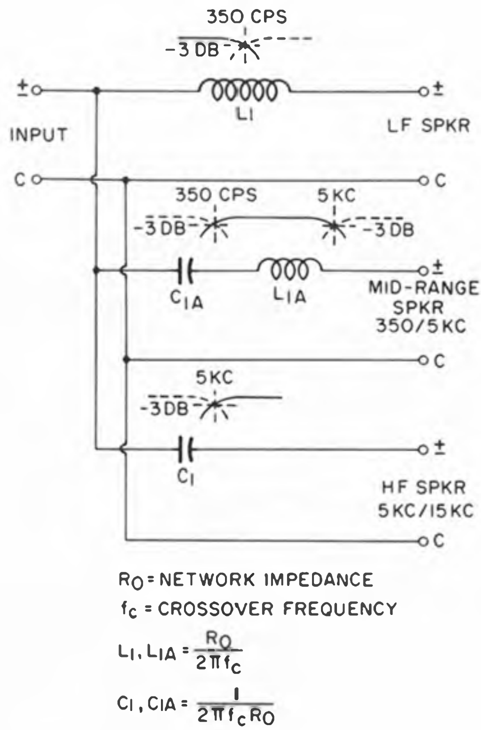


Fig. 2-3. A constant-*k*, three-way, 6-db per-octave crossover network.

manner as for C1 and L1, except for the differenc in frequency (f_c). If the crossover frequency is for 350 cps, the values of C1A and L1 must be calculated for a frequency of 350 cps. Likewise, if a second crossover frequency is to be for 5,000 cps, then C1 and L1A must be calculated for 5,000 cps. Analyzing the frequency-response curves above the filter sections reveals that two crossover points, 350 and 5,000 cps, are established at a point 3 db down from the flat portions of the frequency response. A similar network, only using a 12-db-per-octave cutoff rate, is shown in Fig. 2-4.

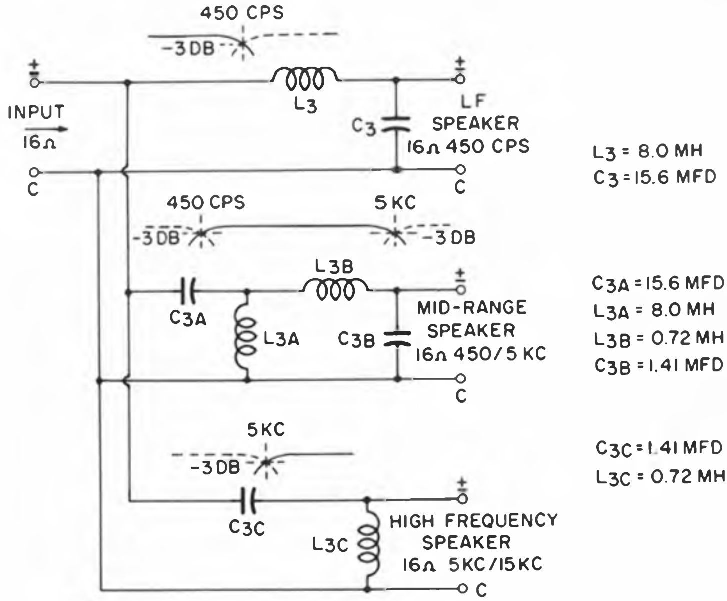


Fig. 2-4. A three-way, 12-db per-octave, 16-ohm impedance, constant-*k* crossover network.

The design of a three-way network and how the two crossover frequencies are formed is best explained by referring to the frequency-response curves above each filter section of the network configuration in Fig. 2-4. The low-frequency section, consisting of inductance L3 and capacitor C3, constitutes a low-pass filter section that cuts off at 450 cps. The midrange section is in reality a bandpass filter consisting of a simple 450-cps high-pass and a 5,000-cps low-pass filter. The circuit elements C3A and L3A form the high-pass, and L3B and C3B the low-pass, filter. These two together form a bandpass filter. Comparing the frequency response of the low-pass filter and the high-pass section of the bandpass filter, note that, both curves are down 3 db from the flat portion of their response and cross over at 450 cps. Thus, the *first* crossover frequency is established.

The output portion of midrange filter L3B and C3B forms a 5,000-cps *low-pass* filter. Circuit elements C3C and L3C, at the lower portion of the configuration, form a 5,000-cps *high-pass* filter. When the frequency responses of these two sections are compared at a point 3 db down from the flat portion of their frequency response, note that a second crossover frequency of 5,000 cps is created. Thus, the network has two crossover frequencies—450 and 5,000 cps.

The design is started by first selecting the circuit-element values for the low-pass filter section. Under the column for 450 cps in Table 2-3, L3 is given a value of 8.0 millihenrys, and C3, 15.6 mfd. Circuit elements C3A and L3A must also cross over at 450 cps, but in an inverse manner. Therefore, their values are equal to those of L3 and C3.

The output portion of the midrange filter L3B and C3B forms a low-pass filter with a cutoff frequency of 5,000 cps. Referring to the 5,000-cps column in Table 2-3, the value required for L3B is 0.72 millihenry and C3B is 1.41 mfd. Circuit elements C3C and L3C form a 5,000-cps high-pass filter and have the same values as circuit elements C3B and L3B, but are inversely connected. When the frequency response of these two sections is compared, at a point where both filter sections are down 3 db, a second crossover frequency of 5,000 cps is created.

If the frequency response of the three sections is plotted as shown in Fig. 2-5, the resulting curve will indicate two crossover frequencies, occurring at 450 and 5,000 cps. Networks using other crossover frequencies can be designed in a similar manner.

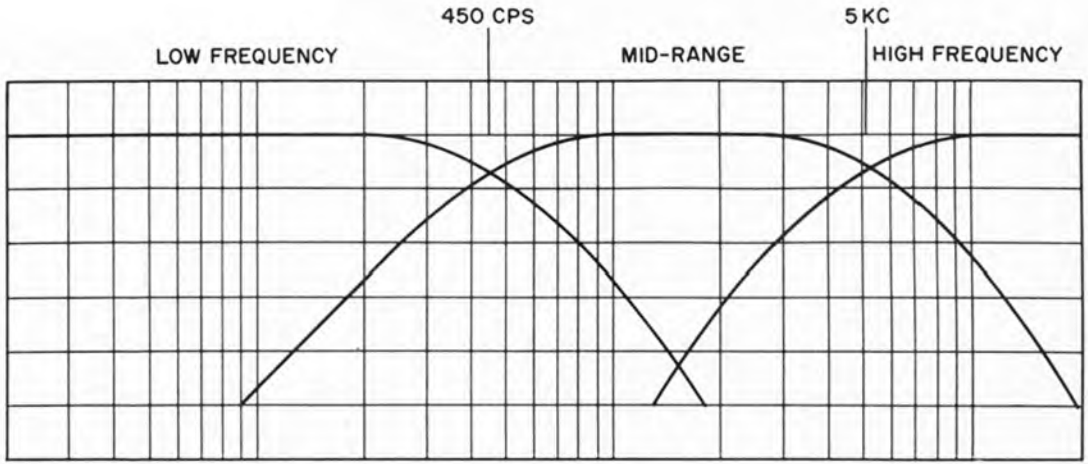


Fig. 2-5. Frequency characteristics of a three-way, 12-db per-octave, 16-ohm parallel network.

2.6 *Four- and Five-Way Networks*

Four-way networks are basically the same as three-way networks, except the four-way networks have three crossover points, all differing in frequency. The electrical characteristics of a typical four-way network are shown in Fig. 2-6. The crossover frequencies for the four-way are lower than that of the three-way network and occur at 200, 1,000 and 3,500 cps. As a rule, for this type of network the high-frequency unit is designed to cover frequencies ranging from below 3,500 cps to 15,000 cps. If the high-frequency unit will not cover this range, an additional network section can be added, as shown in Fig. 2-7. This makes it a *five-way* network, the fourth section crossing over at a frequency of 10,000 cps. The problem can also be solved by connecting the additional high-frequency unit in series with a capacitor to limit the low-frequency response, and then connecting the two in parallel with the high-frequency section of the network, as shown in Fig. 2-8. The value of the series capacitor can be calculated, using the equation for C1 in Fig. 1-5C for a 6-db-per-octave network. The configuration for a five-way network is shown in Fig. 2-9.

In a five-way crossover network, two midrange speakers are employed. The first is called the intermediate, and the second, the midrange unit. Two bandpass sections are necessary to limit the response of the intermediate and midrange units to a given frequency bandwidth. Component values are selected from Tables 2-1 through 2-6. The high-frequency section also employs two units.

The filter section for the first high-frequency unit (Fig. 2-9) uses a 3,500-cps high-pass filter which permits the speaker to reproduce its full frequency response above 3,500 cps. The second high-frequency unit is controlled by a simple 10,000-cps, 6-db-per-octave high-pass filter network connected ahead of the 3,500-cps high-pass filter associ-

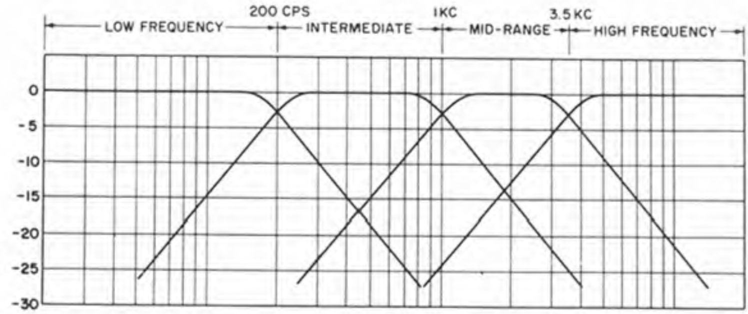


Fig. 2-6. Typical frequency-response characteristics of a four-way, constant-*k* crossover network.

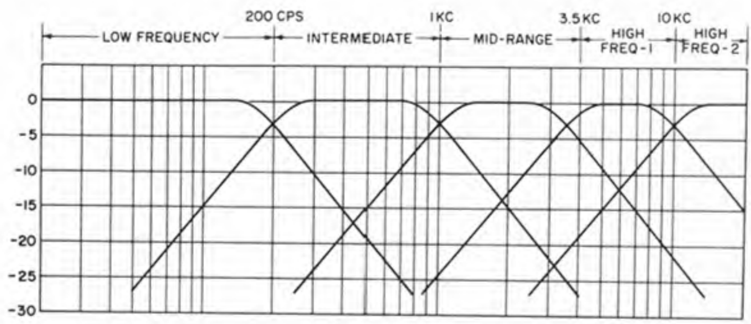


Fig. 2-7. Typical frequency-response characteristics of a five-way, constant-*k* crossover network.

ated with the first high-frequency unit. This will permit the second one to respond to frequencies ranging from 10,000 to 15,000 cps or higher.

Systems employing four or more speakers generally employ two low-frequency units 15 to 18 inches in diameter, especially designed for such use and operating over a range of 20 to 350 cps. Units of this size employ a voice-coil impedance of 32 ohms. The voice coils of the two units are connected in parallel across the output of the low-frequency section to provide a load impedance of 16 ohms.

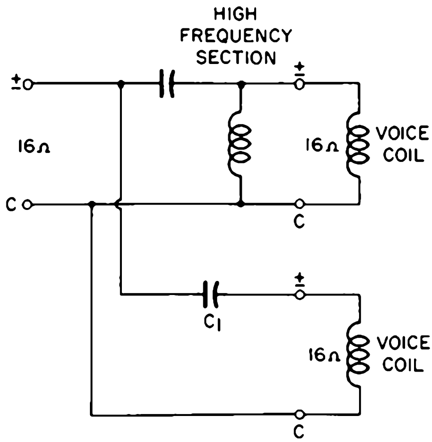


Fig. 2-8. Method of connecting a second high-frequency unit in parallel with the high-frequency section of the network.

Although Tables 2-1 through 2-6 do not include a crossover frequency of 200 cps, the network components may be obtained by selecting the values for 2,000 cps and multiplying them by 10.

Any number of speakers can be connected in parallel, provided the proper impedance match is reflected to the output section of the network by either the voice coils or by impedance-matching transformers. Connecting the voice coils in series to obtain an impedance match, is *not* recommended, however.

2.7 *Three-Way* m*-Derived Networks*

Three-way crossover networks can be designed to use an *m*-derived configuration, as shown in Fig. 2-10. The same general procedure used for designing the constant-*k* is followed, except the circuit values are selected from Tables 2-4 through 2-6.

Each circuit element in an *m*-derived filter has a different capacitance and inductance, whereas in the constant-*k* filter, certain circuit elements are of the same value. The *m*-derived network will require a somewhat greater inductance and capacitance than the constant-*k* type. Also, they will induce approximately 4 db of loss at the crossover fre-

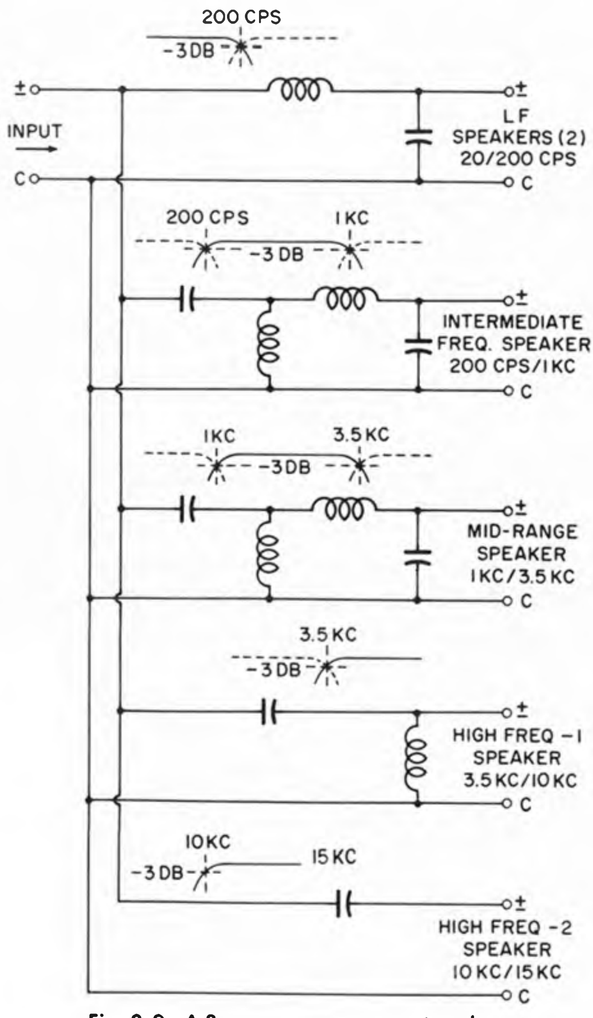


Fig. 2-9. A five-way crossover network.

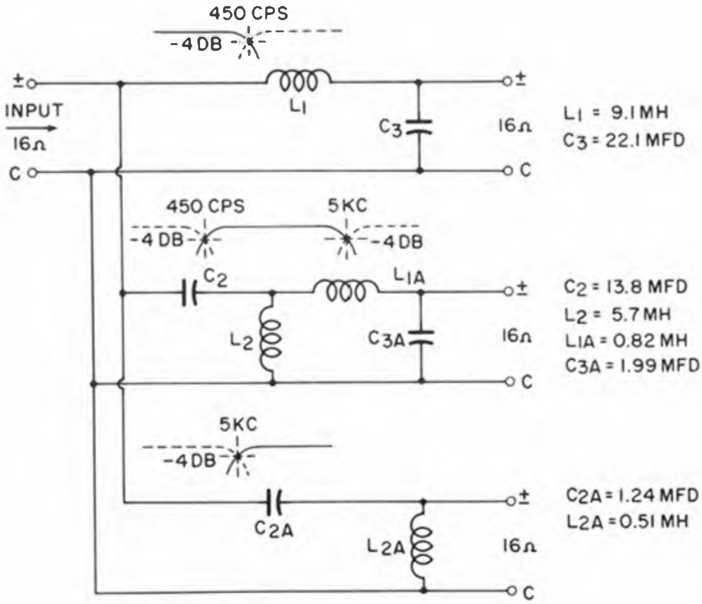


Fig. 2-10. A three-way, 12-db per-octave, *m*-derived crossover network for a circuit impedance of 16 ohms.

quency, rather than 3 db as does the constant-*k* type. However, they will provide a full 12-db-per-octave cutoff rate at the first octave above and below the crossover frequency.

SECTION 3

Network Construction

3.1 Coils

Except for the inductor winding, the over-all electrical and mechanical construction of a speaker crossover network is relatively simple.

The coil-turns winding data in Fig. 3-1 are based on a given wire and coil-form size (shown in Fig. 3-2). The coil-form consists of two *Masonite* sides and a wooden dowel-rod core held together with a nonmagnetic bolt (or rod). The use of a nonmagnetic material such as brass or aluminum is essential for the bolt, because the presence of a magnetic material in the field of the core will affect the inductance. Also, an iron bolt may become saturated during heavy power peaks and thereby cause distortion in the reproduction. Early crossover networks used iron-core coils, which were discarded in favor of the air-core type because of this induced distortion. Air-core coils are linear and will handle high power outputs without inducing distortion. An unwound coil form is shown in Fig. 3-3.

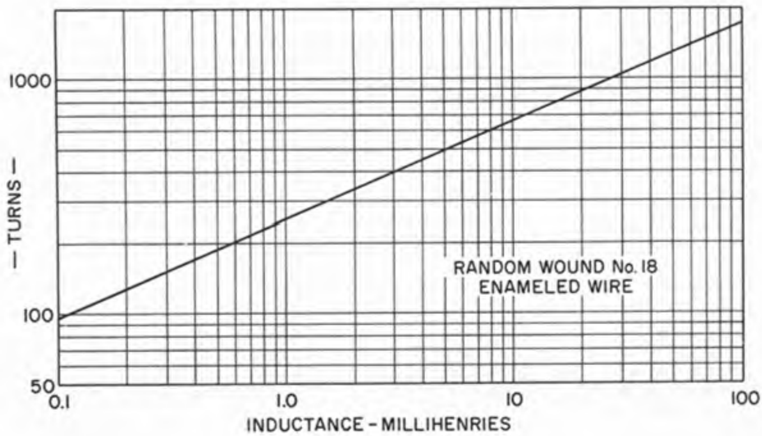


Fig. 3-1. Inductance *versus* turns of wire, using the form in Fig. 3-2.

The dimensions of the coil form, except for the side members, remain the same for all values of inductance. Standardizing on a core diameter and length will permit a given number of turns to be wound on the core for a given inductance, provided the same sizes of wire and insulation are used. The data in Fig. 3-1 are for No. 18 enameled wire. If another gauge of wire or insulation is used, the data will not hold true. Data for the graph in Fig. 3-1 were compiled by winding 1,000 turns on the form and measuring the inductance for each 100 turns. If the dimensions, wire size,

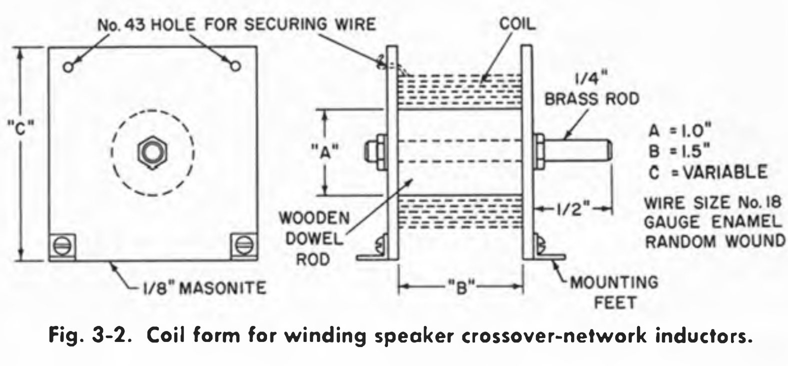


Fig. 3-2. Coil form for winding speaker crossover-network inductors.

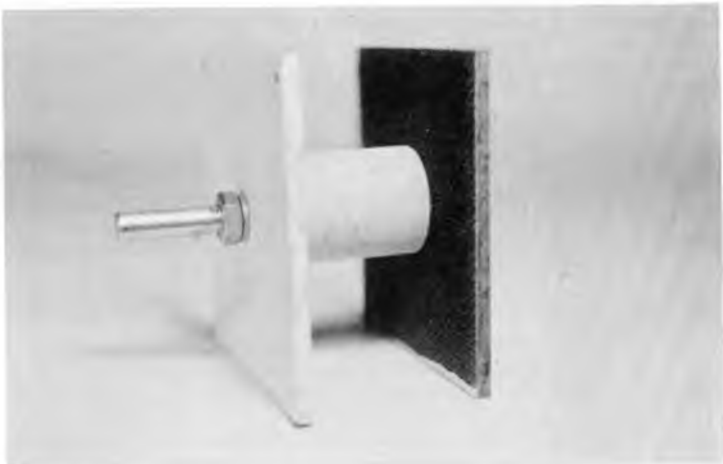


Fig. 3-3. The coil-form assembly bolt or rod should project one-half inch beyond the side member.

and insulation are adhered to, the coils can easily be wound to within ±3% of the specified values. Two completed coils are shown in Fig. 3-4. The dimensions of the side mem-

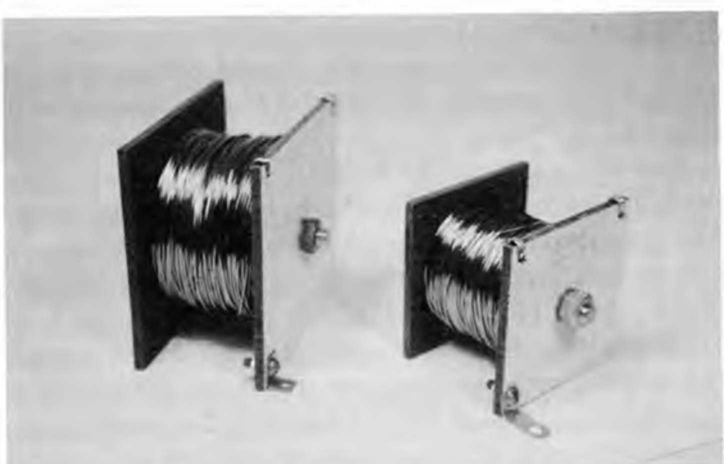


Fig. 3-4. 8.5- and 3.5-millihenry coils.

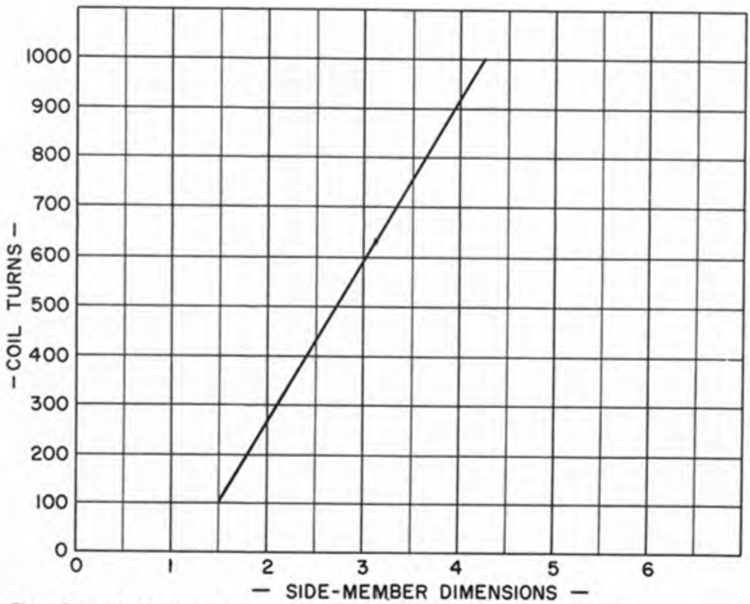


Fig. 3-5. Coil turns *versus* side-member dimensions. Random-wound No. 18 enameled wire.

bers of the coil form will vary, depending on the number of turns in the coil. After the number of turns required for a given inductance has been determined, the graph in Fig. 3-5 should be consulted for the coil-form, side-member dimensions.

Note in Fig. 3-3 that the length of the bolt or rod holding the coil form together is one-half inch longer than required. This permits the end of the bolt to be gripped in the jaws of a hand-drill chuck, which in turn is held in the jaws of a bench vise, as pictured in Fig. 3-6.

Assume the coils for a constant-*k*, constant-resistance, two-way network crossing over at 800 cps and having an impedance of 16 ohms are to be wound. The configuration for the network is to be a series type, as shown in Fig. 1-5B. Referring to Table 2-3 under the 800-cps column, the in-

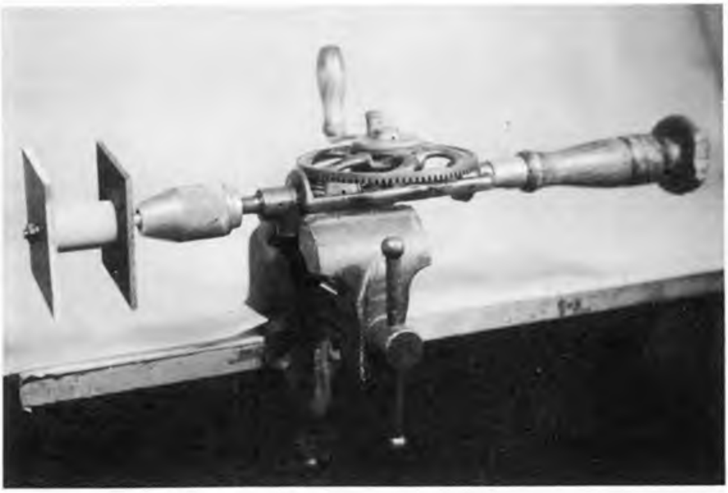


Fig. 3-6. Coil form mounted in hand drill for winding.

ductance required for L2 is 2.3 millihenrys. To determine the number of turns required for an inductance of 2.3 millihenrys, refer to the graph in Fig. 3-1. Enter the graph at 2.3 millihenrys at the bottom; then follow the line upward until it intersects the diagonal one, and read the number of turns required—360—at the left margin.

The dimensions of the coil side member can then be determined from the graph in Fig. 3-5. It indicates that for 360 turns the dimensions will be approximately 2¼" x 2¼". This dimension allows about three fourths inch more than the coil diameter, to provide space for the mounting brackets and holes for securing the ends of the coil winding. The amount of wire, in pounds, required for a given number of turns can be determined from the graph in Fig. 3-7.

The winding is started by scraping the enamel insulation from the starting end of the wire and then threading it twice through the No. 43 hole in the coil-form side member. The first layer of wire can be wound on the core in a close, even

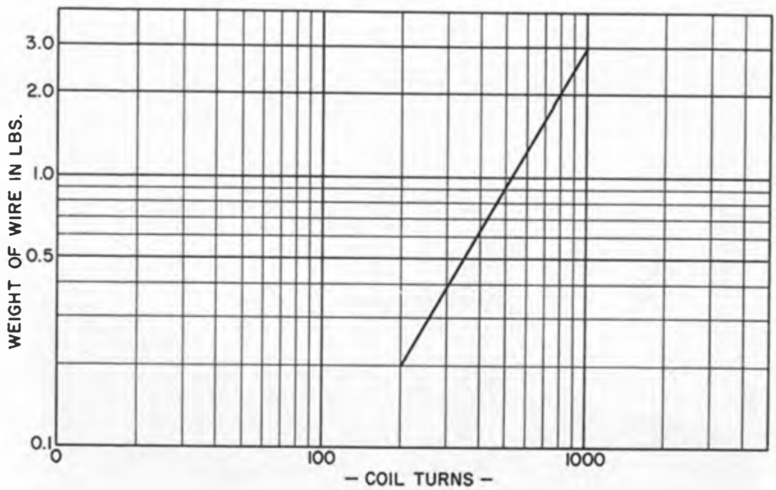


Fig. 3-7. Coil turns versus pounds of wire.

layer. The second and third layers will also wind on smoothly; but as the number of layers is increased, the winding should be random or scramble-wound to keep the layers even. Random or scrambled windings will result in a smaller coil with a higher Q than if the layers are separated by paper. After the required number of turns has been wound, the wire is cut and the enamel again scraped off and threaded twice through the second No. 43 hole in the side member. The two turns in the holes are now soldered together to provide a terminal for connecting the coils to the other elements in the network.

If the coil is to be measured on an inductance bridge, a few extra turns should be added to permit it to be brought to its exact value. (It is always easier to remove a few turns than to add them.) The completed coil can be covered with a layer of black plastic tape to improve its appearance, the bolt cut off, and two small metal brackets attached to the lower edge of the side member for mounting the coils.

Fig. 3-8. A two-way, 800-cps, 16-ohm, 12-db per-octave crossover network.

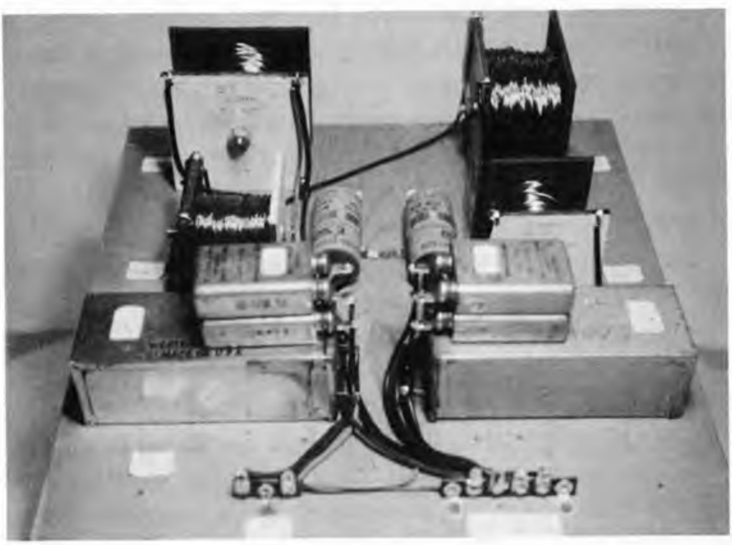


Fig. 3-9. A three-way, 16-ohm, 12-db per-octave crossover network. Crossover is at 450 and 5000 cps.

If it is necessary to add turns to a coil, about one-eighth inch of enamel is scraped from the wire, which is then tinned with solder. The wire to be added is treated in a similar manner. A small piece of plastic tubing is slipped over one wire, and the ends of the wires are brought together in parallel and soldered. The plastic tubing is then passed over the soldered ends and the winding is continued. A completed 16-ohm, 12-db-per-octave two-way network crossing over at 800 cps is pictured in Fig. 3-8, and a three-way network crossing over at 450 and 5000 cps is shown in Fig. 3-9.

3.2 Capacitors

In Section 1.6 the use of electrolytic capacitors for crossover networks was discussed at some length. The first choice of capacitors are those with a paper or oil dielectric. However, since large banks of such capacitors are expensive and are rather hard to obtain in the exact values specified, electrolytic capacitors are more practical. The dual electrolytic capacitor units shown in Fig. 3-10 are easily obtainable and serve quite satisfactorily. The principal drawback to the use of electrolytic capacitors is their wide variation in capacitance—20 to 30 per cent from their rated values is not uncommon. In some instances this can be used to advantage because they can be built out to their specified values.

Section 1.6 also mentioned that nonpolarized electrolytic capacitors were the most desirable. Since such capacitors in small values are not readily obtainable, dual units like those in Fig. 3-10 will do quite nicely if connected in series. Dual-capacitor units of 10, 20, 30, 40, and 50 or even higher are stock items. As mentioned earlier, when two capacitors are connected in series, the total capacitance is one-half that of a single unit. Thus, a dual unit of 25/25 mfd con-

Fig. 3-10. A typical dual electrolytic capacitor using a common negative connection.

nected in series would have a total capacitance of 12.5 mfd. Because the capacitance in the network is important to the crossover frequency, it will be necessary to measure the capacitance of the two units in series. This can be done with a capacitance bridge like the one used in radio and television servicing.

Dual electrolytic capacitors generally have three leads—two positive and a common negative, as shown in Fig. 3-11. Only the two positive leads are used. The negative poles are tied together internally and brought out to a single negative lead. In some dual units, however, separate negative and positive leads are brought out and the two negative leads are connected together. In a nonpolarized electrolytic capacitor, the total capacitance is measured from one positive lead to the other.

In building up the capacitor banks, a value of 1 or 2 mfd below the specified value is selected and then built out to

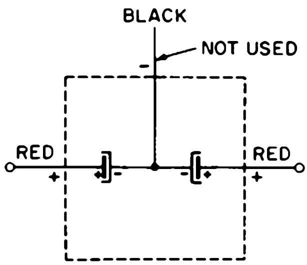


Fig. 3-11. Internal connection of a dual electrolytic capacitor.

the required value, using small paper or oil-filled capacitors as illustrated in Fig. 3-12.

As mentioned previously, connecting a small paper capacitor in parallel with the electrolytic capacitor serves two purposes: it builds out the bank to the required capacitance, and it decreases the rising impedance of the electrolytic capacitor at the higher frequencies. This results in a steeper cutoff characteristic. For very large values of capacitance,

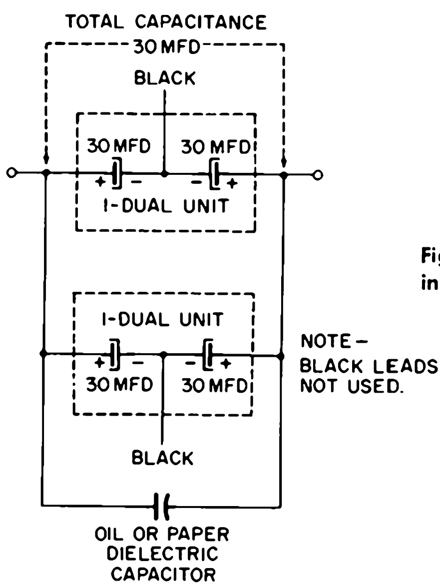


Fig. 3-12. Method of connecting the electrolytic capacitors to obtain the proper capacitance.

Fig. 3-13. Two single electrolytic capacitors connected back-to-back to form a nonpolarized capacitor.

several electrolytic capacitors must be connected in parallel, as shown in Fig. 3-12. The total capacitance should be held to within ±3%.

Single electrolytic capacitors similar to those in Fig. 3-13 can be used if desired, rather than dual units. In some instances they may be more satisfactory in reaching the desired value of capacitance. The two single units shown are connected back-to-back, with the two negative leads connected together. They then function as a nonpolarized capacitor.

3.3 Mounting Components

After the coils have been completed and the capacitor banks built, the components are mounted on a wooden baseboard, as shown in Figs. 3-8 and 3-9. The coils are mounted at right angles to each other to prevent inductive coupling between them. The capacitor banks can be mounted in any convenient position. No. 18 wire or larger is employed for interconnecting the circuit elements. Tie points are used for the external connections to the amplifier and speakers.

SECTION 4

Network Testing and Use

4.1 General

After a crossover network has been completed, only a few simple tests are necessary to determine if it is functioning correctly. The most important of these tests is measurement of the frequency response. This will indicate whether the crossover frequency falls at the correct place in the frequency spectrum and is within the design tolerance of ± 5 per cent.

Measuring the frequency response of the network will require the use of an audio oscillator, an amplifier, a variable or fixed attenuator of 30- to 40-db loss, and a vacuum-tube voltmeter. When measuring the frequency characteristic of a crossover network, be sure the amplifier driving the network does not induce a frequency characteristic of its own. Otherwise, the measurement at the output of the network will not reflect the true response of the network, but will be the amplifier and network response combined.

A second measurement, although not necessary, is the insertion loss, or the loss of power caused by connecting the network in the output of the amplifier. This loss is caused by the DC resistance of the inductors and the shunt reactance of the capacitors within the network. As a rule, the insertion loss of a well-designed network will measure 0.5 to 1.0 db. Insertion-loss measurements are made in the flat portion of the network frequency response, and are not to be confused with the loss incurred at the crossover frequency. The higher the insertion loss of the network, the more power dissipated in the network, and thus, the less power available for driving the speakers.

The insertion loss of a network can be reduced by using a larger wire size than No. 18. However, the larger wire becomes rather difficult for the experimenter to handle, unless special coil-winding equipment is available. An insertion loss of 0.5 to 1.0 db is not serious in a home sound system. However, in a large commercial system employing 100 watts of power, this would mean a loss of approximately 25 watts. To obtain a power output of 100 watts under these conditions, the power output of the amplifier system would have to be increased to compensate for the loss of power in the network.

4.2 Two-Way Parallel-Configuration Measurement

To eliminate the frequency characteristic of the driving amplifier from that of the network, the amplifier high- and low-frequency controls (if any) are adjusted for a flat frequency response. Most amplifier controls have a position marked for a flat response, and the controls are set to this mark. A final adjustment is made in the following manner:

Terminate the output winding of the amplifier, as shown in Fig. 4-1, using a noninductive resistor R_L with a value equal to the rated output impedance of the amplifier. Connect a vacuum-tube voltmeter across the R_L as shown, taking care to connect the *low potential*, or ground side, of the meter to the ground, or common, side of the output winding.

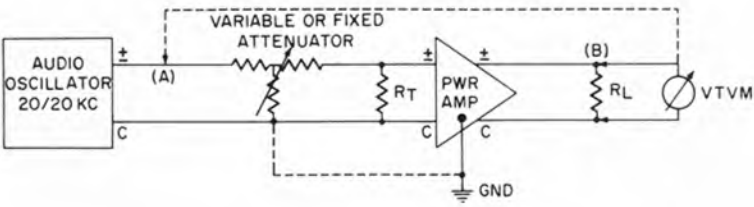


Fig. 4-1. Connections for measuring the frequency response of an amplifier.

Connect the audio-oscillator output to the amplifier input through a variable or fixed attenuator of 30- to 40-db loss. The use of an attenuator between the output and input circuits of the amplifier accomplishes three purposes: (1) It attenuates the oscillator signal voltage to a level suitable for the input of the amplifier. (2) It provides an impedance match between the oscillator and the amplifier. (3) It increases the signal-to-noise ratio of the oscillator signal by attenuating the internal noise and hum. Reducing the oscillator output voltage by using an external attenuator permits the oscillator to be operated at a higher output level and, at the same time, reduces the signal voltage to the amplifier input. This makes it easier to measure the oscillator output voltage with a vacuum-tube voltmeter.

The attenuator can be dispensed with if the output impedance of the oscillator is sufficiently high and the circuitry incorporates a variable-output voltage control. In this instance, the oscillator output is connected directly to the amplifier input circuit.

Set the audio oscillator to a reference frequency of 1,000 cps, and adjust the output level of the amplifier, by means of its volume control, for a reading of 5 volts on the vacuum-tube voltmeter (if the meter is calibrated in decibels, set it to zero dbm, using the +20-dbm scale). Leave the amplifier volume control at this setting for the balance of the measurement. Sweep the oscillator across the entire frequency band and adjust the low- and high-frequency amplifier controls for the most uniform frequency response, as indicated by the vacuum-type voltmeter. For a true frequency response of the amplifier, the oscillator output voltage must be maintained at a constant value for all frequencies.

The output voltage from an oscillator is seldom constant. Therefore, each frequency of interest must be set to the same value as the reference (1000-cps) frequency. This is done by using a second vacuum-tube voltmeter, or by switching the same meter from the oscillator output to the output section of the network as required. The oscillator output voltage should be measured at the input to the attenuator (if one is used), because the voltage at this point will be higher and hence easier to measure.

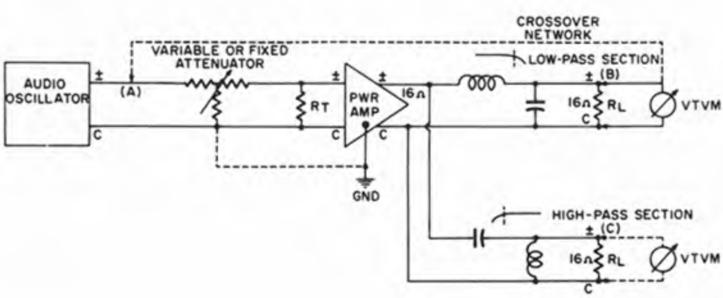


Fig. 4-2. Connections for measuring the frequency characteristics of a two-way crossover network with a 16-ohm impedance.

With the amplifier controls adjusted for a flat frequency response, (within ±0.50 db with reference to 1,000 cps), remove terminating resistor R_L and connect the network in its place, as shown in Fig. 4-2.

Several precautions must be observed when connecting the network for measurement. If the driving amplifier employs negative feedback taken from the output winding of the output transformer, one end of the winding will be *grounded* to the amplifier chassis. If a network of the parallel filter type (Fig. 4-2) is being measured, the common side of the network elements must be connected to the grounded, or common, side of the amplifier output winding. If the network is of the series configuration (Fig. 4-6), the input terminal going to the high-pass filter section must be connected to the chassis ground. It is also important that the network be connected to the correct impedance tap on the amplifier output. Both output sections of the network must be terminated in a resistive load during the measurements. Vitreous wirewound resistors with a power rating of 10 to 20 watts make ideal terminating resistors. The small inductance of these resistors will have no ill effect on the measurement; for all practical purposes they can be considered noninductive.

It is also desirable that a good physical ground be connected to the amplifier chassis before starting the measurement, to prevent any tendency toward oscillation. If the input circuit of the amplifier is not grounded, a ground should be connected to the *lower* side of the input attenuator, as shown by the dotted lines. This will prevent leakage in the attenuator at higher frequencies.

Connect a terminating resistor, R_t, of the same value as the attenuator impedance, across the input to the amplifier. The network is now ready for measurement.

First, measure the frequency response of the low-pass filter section. Connect the vacuum-tube voltmeter across the output of the oscillator to set the reference voltage, and then switch to the output termination of the low-pass section (Fig. 4-2).

Assume a two-way, 16-ohm network crossing over at 800 cps is to be measured. Set the audio oscillator to a reference frequency of 40 cps. Adjust the output level of the amplifier at this frequency to obtain a reading of +20 dbm (7.74 volts) on the meter, or a little less than 5 watts output across 16 ohms. Slowly sweep the oscillator upward in frequency, taking care to keep its output voltage at the same value as the 40-cps reference voltage. As the frequency of the crossover in the network is approached, the reading of the vacuum-tube voltmeter will fall off, requiring the sensitivity of the meter to be increased. Note readings for a sufficient number of frequencies to enable you to plot the crossover characteristic, as shown in Fig. 4-3.

The roll-off for the first octave above the crossover frequency (1600 cps) may be slightly less than the designed rate of cutoff, but will approach the designed rate after the first octave.

After tabulating the results of the measurement, transfer the vacuum-tube voltmeter to the high-pass filter section, leaving the low-pass section terminated in its resistive load R_L. Now set the audio oscillator to 10,000 cps and again adjust the amplifier output voltage to read the same value as the 40-cps reference voltage used when measuring the low-pass filter section. This time, make the frequency run *downward,* to a point two or more octaves (200 cps) below the crossover frequency. Again remember that each time the oscillator frequency is changed, its output voltage must be set for the same value as the reference voltage. As the cutoff frequency is approached, the frequency response will again fall off, as it did for the low-pass section. Tabulate the result of the two measurements on semi-logarithm paper. If the crossover frequency falls within ±24 cps

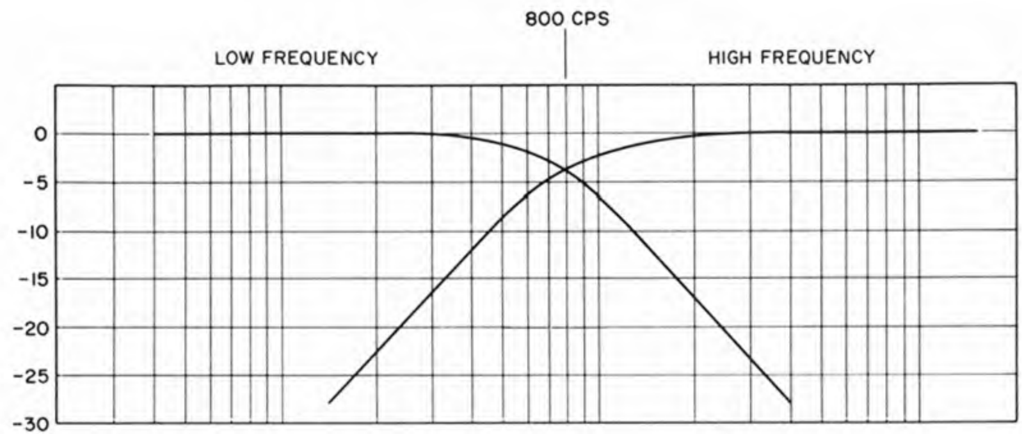


Fig. 4-3. Frequency characteristics of a two-way, 12-db per-octave, 16-ohm series network.

(3%) of the 800 cps, it is quite satisfactory; it makes little difference if the crossover is 776 or 824 cps.

4.3 Three-Way Parallel-Configuration Measurement

The measurement of the frequency characteristics of a three-way crossover network is the same as for a two-way network except that two additional measurements will be required. To measure a three-way network, connect the audio oscillator, amplifier, and network as in Fig. 4-4.

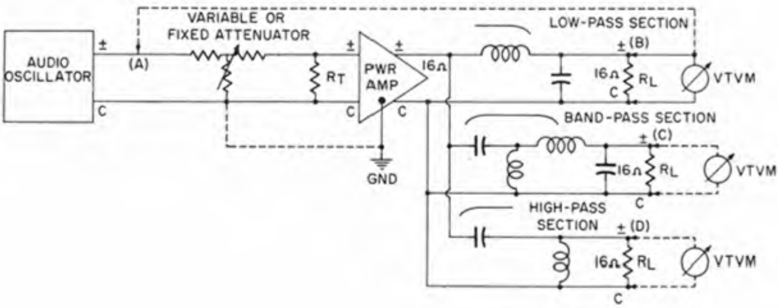


Fig. 4-4. Connections for measuring the frequency characteristics of a three-way crossover network with a 16-ohm impedance.

As an example, if the network crosses over at 450 and 5,000 cps, the low-frequency section is measured as described for the two-way system in Section 4.2. The midrange section in a three-way network is measured, using a reference frequency of 2,000 cps and moving downward in frequency for two or more octaves. Return to the 2,000 cps and again measure the midrange section upward in frequency for two or more octaves. The 5,000-cps section is measured like the two-way network, starting at 10,000 cps or higher and then progressing downward in frequency. The results of the four measurements are tabulated and then plotted (refer to Fig. 2-5).

Crossover networks employing more than three sections are measured in the same manner as described for the three-way network, except the reference frequency is changed to one that will fall in the flat portion of the frequency characteristic.

4.4 Two-Way Series-Configuration Measurement

Series-type configurations are measured in a manner similar to that described for the two-way parallel-system network. The oscillator, amplifier, and network are connected as shown in Fig. 4-5. Although the series configura-

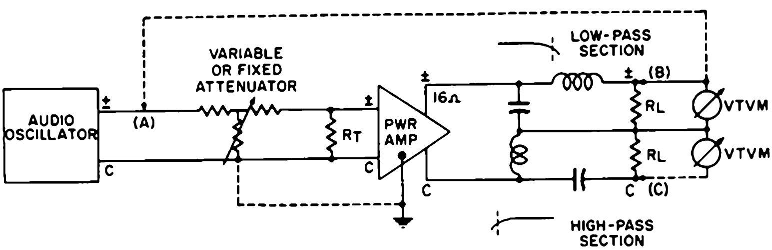


Fig. 4-5. Connections for measuring the frequency characteristics of a two-way, series-type network with a 16-ohm impedance. (The procedure for the measurement is the same as for a parallel network.)

tion appears to be balanced, no ill effects will be noted if the high-frequency section is connected to the grounded side of the output circuit. The results of the measurement are plotted as for the parallel configuration, as shown in Fig. 4-3.

4.5 Insertion-Loss Measurement

The insertion loss of any network is caused by the series DC resistance of the coils and the shunt reactance of the capacitors. To measure the insertion loss, connect the network as in Fig. 4-6. The only difference in the connection for this measurement and the previous one is the way the vacuum-tube voltmeter is connected and used.

First, measure the loss of the low-pass section as follows: Set the oscillator at least two octaves below the crossover frequency. Set the output level of the amplifier to exactly 9 volts (approximately 5 watts in 16 ohms), and connect the vacuum-tube voltmeter to point A. Then connect the meter to point B and again note the output voltage. The difference beween these two measurements can then be equated to determine the insertion loss of the low-pass section.

The high-pass section is measured in a similar manner, except the oscillator frequency is set two octaves above the crossover frequency.

As an example, assume the voltage at the output of the network is 8.5 volts, for a value of 9 volts at the input. The insertion loss can now be calculated:

$$\left.\begin{aligned} P1 &= \frac{E^2}{R} = \frac{9^2}{16} = \frac{81}{16} = 5.05 \text{ watts} \\ P2 &= \frac{E^2}{R} = \frac{8.5^2}{16} = \frac{72.25}{16} = 4.5 \text{ watts} \end{aligned}\right\} 0.5 \text{ watt loss}$$

where, P1 is the power measured at the input to the network, P2 is the power measured at the output.

The insertion loss in decibels may be calculated:

$$db = 10 \log_{10} \left(\frac{P1}{P2} \right)$$

$$= 10 \log_{10} \left(\frac{5.05}{4.5} \right)$$

$$= 10 \log_{10} \times 1.121 = 10 \times 0.051 = 0.510 \text{ db}$$

The insertion loss of 0.5 db is of little concern with systems having up to 60 watts of power.

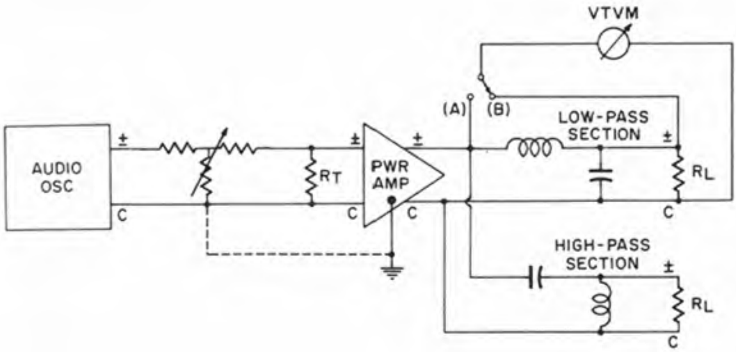


Fig. 4-6. Connections for measuring the insertion loss of a two-way network. (Series-type networks are measured in a similar manner.)

4.6 External Controls

It is common practice in multiple speaker systems to include one or more variable controls for adjusting the acoustical output level of the midrange and high-frequency units. This is necessary to compensate for the difference in efficiency between the units and to obtain a smooth transition from one section of the system to the other. Three different types of controls are available for this purpose, as shown in Fig. 4-7: the conventional potentiometer (Fig. 4-7A), the "L" pad (Fig. 4-7B), and the "T"-type attenuator (Fig. 4-7C). The most desirable of the three is the "T"-type attenuator, for the following reasons. The potentiometer (A) must have a DC resistance equal to at least five times the output impedance of the network section it terminates. This high resistance is necessary to prevent loading the network output circuit to a value below its normal load impedance when the control is fully on.

To analyze the action of the potentiometer when it is connected to the network, assume the network has an output impedance of 16 ohms. A potentiometer having a resistance of 80 ohms (5×16 ohms) will be required. With the movable contact of the control fully on, the output section of the network sees the potentiometer resistance in parallel with the voice-coil impedance of:

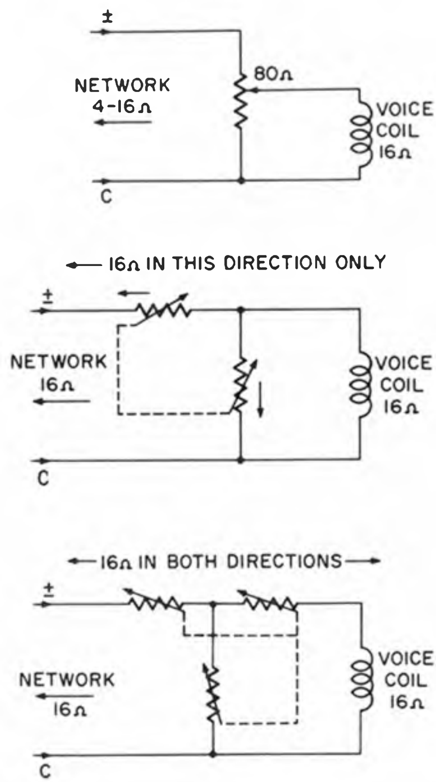
$$\frac{16 \times 80}{16 + 80} = \frac{1280}{96} = 13.3$$

with the control at the halfway point, or 50 per cent of its resistance, the parallel load impedance is:

$$\frac{16 \times 40}{16 + 40} + 40 = 51.4 \text{ ohms}$$

Thus, the output of the network never sees its correct load impedance. If possible, avoid using this type of control. The objection to the variable loading effect of the potentiometer can be overcome somewhat by using the "L"-type attenuator in Fig. 4-7B. This device has two variable arms which are varied inversely with respect to each other. As the series arm increases in value, the shunt arm decreases; thus, a more or less constant load impedance is reflected to the output of the network. Although this control is better than the potentiometer type, it still has a drawback—it presents only a constant-load impedance to the network. As the attenuation is increased, the shunt arm—in parallel with the speaker voice coil—will approach zero resistance. At 50 per cent of its loss, the shunt value may be only a fraction of an ohm.

The defects of both the potentiometer and the "L" pad can be eliminated by using the "T"-type attenuator in Fig. 4-7C. A "T"-type attenuator consists of three arms which are mechanically ganged so they can be varied simultaneously. As the attenuation is increased, the two series arms increase in value, while the shunt arm decreases. Therefore, the impedance seen by the speaker voice coil and the network output circuit are constant, regardless of the amount of attenuation.



(A) Potentiometer.

(B) "L" pad.

(C) "T"-type attenuator.

Fig. 4-7. Three types of controls for adjusting the acoustical output level of the midrange and high-frequency units.

When either the "L"- or "T"-type attenuator is used, its impedance is the same as the network impedance; the potentiometer is the only one that has a higher value.

4.7 Impedance Matching

Correct impedance matching of the speaker to the crossover network is essential for good reproduction and for maximum transfer of power from the amplifier to the speaker system. If a speaker does not match the output impedance of the crossover network, the impedance-matching autotransformer or conventional two-winding transformer described in Section 2.3 can be used. Voice coils can also be connected in parallel if they are of the same impedance. The parallel combination will reflect the correct load impedance to the network.

4.8 Speaker Phasing

To properly reproduce program material, the diaphragms of a multiple-speaker system must be in acoustic phase with each other. That is, all the diaphragms must move in the same direction at a given instant.

This is accomplished by noting the manufacturer's marking and connecting the ± terminals to the ± connections of the crossover network. If the units are unmarked, they can be phased electrically by connecting a flashlight cell to the voice-coil terminals in a given direction. The diaphragm will then move either backward or forward. Note the direction of the motion, and mark the voice-coil leads to correspond to the battery terminals for a given direction. The final phasing is accomplished by a listening test.

Phasing multiple speaker systems is sometimes difficult, and it is quite easy for the listener to become thoroughly confused as the test progresses. As a rule, an out-of-phase speaker system will manifest itself by having a good low- and high-frequency response, but the over-all response will lack presence. This will be particularly true when one is listening to a male voice; on a system employing a crossover frequency of 800 cps, the voice will appear to move from one speaker to the other.

The acoustic phasing of a two-way system can be determined by applying to the system an oscillator frequency equal to that of the crossover network. Then find the exact center of the crossover by slowly rocking the oscillator over a small band of frequencies above and below the crossover frequency. Meanwhile, have a listener move from the low- to the high-frequency unit. If the system is in phase, the tone will be smooth as it passes through the crossover frequency and from one unit to the other. If the system is out of phase, a null point (dead spot) will appear somewhere between the units. The null point is caused by the cancellation of the out-of-phase signals as they reach the ears of the listener simultaneously.

Out-of-phase conditions can be corrected by reversing the voice-coil leads to one unit—but not both. When the phasing is correct, the signal will appear uniform when passing from one unit to the other.

If the speaker system will permit, the phasing can be further improved by moving the high-frequency unit slightly in front of or behind the low-frequency unit.

A more scientific method of phasing is to place a microphone, connected to an amplifier and vacuum-tube voltmeter, in front of the system. Apply a signal as previously described, and adjust for equal output from each section, as indicated by the vacuum-tube voltmeter. When the units are balanced, reverse the voice-coil leads to one unit and note the output level. If they are in phase, the output will be maximum; if out of phase, the level will drop or may be near cancellation. The high-frequency unit can now be properly placed by sweeping the oscillator across the frequency spectrum and noting when the smoothest response is obtained. Do not interpret the frequency response obtained as being the true response of the system; many variables will be induced because of reflections from surrounding objects, microphone and amplifier characteritsics, etc. The final proof of any speaker system is its quality of reproduction. After phasing the speakers, mark the voice-coil leads to facilitate future reconnection.

A three-way speaker system is phased like the two-way system, except it is somewhat more difficult because of the added section. Many times the listener will develop listening fatigue before the acoustic phasing period is finished. Since listening fatigue only leads to confusion, further listening tests should be postponed.

4.9 Control Adjustment

After the system has been electrically and acoustically phased, it is ready for use, except for adjustment of the midrange and high-frequency controls.

For a two-way system, the adjustment is started by setting the high-frequency control to about half its attenuation range. Apply to the system a musical selection having a wide frequency range and a heavy low end. Adjust the output level of the amplifier to reproduce the low frequencies at a fairly good room volume. Adjust the high-frequency control for an acoustical balance between the low- and high-frequency sections. Make this test in the same room in which the speaker system is to be installed, if possible. The final reproduction should be smooth and should not accentuate either the low or the high frequencies.

To adjust the midrange and high-frequency controls in a three-way system, set them to half their range of attenuation and adjust the amplifier output for a heavy low-frequency reproduction. Then adjust the midrange for a near balance against the low-frequency section, and balance the high-frequency control against the midrange frequencies.

Readjust the two controls for a wide-range balance over the entire frequency spectrum of reproduction. The final quality of reproduction should have a wide range without undue accentuation of the midrange or high frequencies.

Although a good balance can be obtained with only one musical selection, a compromise is generally made for the best over-all reproduction from several selections of known quality.

As a final listening test, reproduce a vocal selection of intimate quality. The quality of reproduction should create the illusion that the singer is present in the room with the listener. This feeling of presence can be increased by raising the output level of the midrange unit.

If the system is moved to another location, the control may require rebalancing to compensate for the difference in acoustical characteristics. More midrange and high-frequency response will be required if the room is heavily draped. The midrange and high-frequency sections must always be balanced against the low-frequency response. If not, the system will appear to have insufficient low-frequency reproduction.

4.10 Electrostatic Speakers

If an electrostatic speaker is to be used, it should have a high-pass filter section with the cutoff frequency recommended by the manufacturer. Connect the electrostatic unit to the output of the network section, in parallel with the resistive termination, as shown in Fig. 4-8. Adjust the acoustical output level of the electrostatic unit as described in Section 4.9. If it has its own network, connect the unit directly across the amplifier output terminals.

Electrostatic speakers impose a capacitive load on the output of the amplifier. If the amplifier has any tendency to be unstable, the capacitive load of the electrostatic unit may cause it to break into oscillation, particularly at the low frequencies. If distortion is observed, disconnect the electrostatic unit from the system and again listen for distortion.

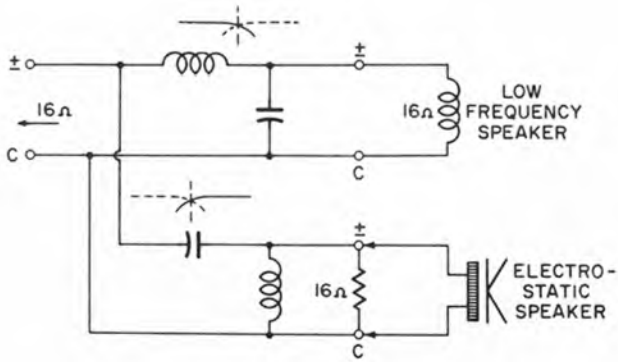


Fig. 4-8. A two-way crossover network using a compression and an electrostatic speaker.

If oscillation occurs only when the electrostatic unit is used, consult the amplifier manufacturer for further instructions on how to use the amplifier and an electrostatic speaker together.

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all about CROSSOVER networks

by HOWARD M. TREMAINE

All About Crossover Networks was written for one person, the individual—whether technician, hobbyist, or audiophile—who wants the best possible reproduction from his hi-fi system. Many times a good speaker system is blamed for poor reproduction, when a properly designed crossover network would have saved the day. *All About Crossover Networks* covers the basic principles, design, construction, and testing of crossover networks. In addition, it contains handy charts and tables to make it easy for you to compute component values. Also included are simple instructions for the construction, testing, and phasing of the entire speaker system. Although written for the technician or audiophile with some background in electronics, this book supplies all the information the neophyte needs to build his own crossover network.

Mr. Tremaine is perhaps most famous for his monumental 1280-page work on audio, *The Audio Cyclopedia*. No one is better qualified to write a book on crossover networks. For 23 years Mr. Tremaine was a sound engineer in the motion-picture industry, and is now Chief of the Sound Division, USAF, Lookout Mountain Laboratory, Hollywood, Calif. He has been a "ham" since before the first World War. Shortly thereafter, he and his father manufactured wireless apparatus in Philadelphia. His degrees and titles are as lengthy as the bookshelves which hold his other writings, including *Attenuators, Equalizers and Filters*, and seventeen papers on recording and audio engineering. Among his honors are a Fellow of the Audio Engineering Society; Active Member of the SMPTE, the International Sound Technicians, Local 695; a Registered Electrical Engineer; an Honorary degree, Doctor of Science; and many others.

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