A STUDY OF THE OPERATION AND CONSTRUCTION OF SPEAKER SYSTEMS/ENCLOSURES

THESIS

Presented to the Graduate Council of the
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Fulfillment of the Requirements

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MASTER OF SCIENCE

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INTRODUCTION

The desire for acoustical excellence has occupied man's mind almost immediately from the time he first produced an artificial or transcribed sound. The problems of reproducing natural sound are ones that must be solved by using data from the areas of physics, acoustics, and electrical research. The technology that produces high quality speaker components will not necessarily result in the production a commercially successful speaker system. Enclosures that house a system must be aesthetically pleasing to the consumer if they are to be marketed successfully. At present, even with his seemingly limitless technological resources, man can only imitate to a fair degree perfectly natural sound. Improvements in the technology of electronic miniaturization, as well as the uses of new materials and manufacturing processes, have made the state of the art in the hi-fidelity industry dynamic and constantly improving.

Alexander Graham Bell's invention of the telephone in 1876 was closely followed by his experiments with the aural and spatial dimension of sound, or in other words, the ability of speakers to reproduce and the ear to distinguish depth perception and direction of sound. The modern era of sound was begun in 1919 by Peter Jensen and Edwin L. Pridham with the invention of the moving coil magnetic loudspeaker (10, p. 5).

Experiments on sound reproduction and hi-fidelity conducted from the early 1930's by Bell Laboratories up to the modernists such as Klipsch and Bose have proven that a loudspeaker alone cannot reproduce the full range of audible frequencies (3, 8). The hi-fidelity loudspeaker must have some help from the baffle or enclosure. Just as a violin body or a tuba bell helps resonate or baffle the instrument's sound, an enclosure of some type nearly always must be employed in combination with the loudspeaker to improve frequency response.

As in most dynamic industries, the science of acoustical reproduction is a very technical and sophisticated business. The state of the art is such that it could be a mistake to build blindly an enclosure for a speaker system without investigating some of the literature or data available on the subject. There is much practical knowledge to be gleaned from a project such as the building of a speaker enclosure system. If properly supervised and supplied with the correct and current information, the student can incorporate aspects of physics, mathematics, and furniture design into the learning experience of enclosure construction.

Purposes of Study

The purposes of the study are as follows:

1. To delineate the functions of the different component parts of a loudspeaker so as to show its working relationship with the enclosure or baffle.

2. To analyze the basic types of speaker enclosure designs and to define their application for use in woodworking shop projects.

3. To explore the skills and knowledge needed to build correctly a highly functional speaker system cabinet.

4. To present these construction techniques in such a way as they might be helpful to the prospective builder of a speaker system enclosure.

5. To provide a helpful guide for the design and construction of hi-fidelity cabinetry and to help the builder avoid needless and costly mistakes of acoustic and aesthetic design.

Basic Assumptions

This study is being made on the basis of the following assumptions:

1. That hi-fidelity sound reproduction in the United States has evolved to a point that it is no longer a luxury item available to the few audiophiles.

2. That the growing percentage of component sound equipment represented by annual sales suggests that people are now and will continue to be interested in quality reproduction of sound.

3. That to build a hi-fidelity stereo enclosure cabinet involves the application of acoustical theory, physics, furniture design, and cabinet making techniques.

Limitations of the Study

For the purpose of this study, the following limitations were necessary:

1. The study was limited to basic loudspeaker operation theory and basic enclosure design theory.

2. No attempt was made to include the complicated mathematical physics of loudspeaker operation.

3. No attempt was made to include exotic or experimental enclosure designs in the part of the study dealing with construction techniques.

4. The electronics covered in this study is only sufficient to make adequate explorations of acoustical circuits and speaker systems operations.

Definition of Terms

For the purposes of clarification within this study, the following terms were defined:

Loudspeaker is an electroacoustic transducer that radiates acoustic power into the air with essentially the same waveform as that of its electrical input.

Speaker system is a combination of two or more speakers working together within the confines of a baffle or enclosure.

Baffle is a shielding structure that is used to lengthen the path of a loudspeaker's transmission wave.

Enclosure is a housed baffle.

Loudspeaker efficiency is a ratio of acoustic output to electrical input.

Resonant frequency is the frequency at which a body naturally tends to vibrate when set in motion.

Transient response is the amount of time it takes for a speaker to reach full amplitude in response to an instantaneous signal input. It is also the amount of time necessary for the speaker to decay or cease vibrating after a signal input is removed.

Damping factor depends upon how well an amplifier or enclosure system can control oscillations of a speaker after the initial bump of an input signal.

Q is damping to unity or, in other words, critically damped.

Critically damped means a speaker system is properly adjusted to a particular listening area so as to eliminate any boominess or hangover of transients.

d-c represents direct current or current flowing in one direction.

Alnico represents aluminum, nickel, and cobalt compounded for use in permanent magnets.

Sine wave is a pure tone used for testing speakers.

Electronic crossover is used in two-way and three-way speaker systems to channel certain frequencies to a particular speaker.

Fletcher Munson effect states that sound in the 3500 cps region has more loudness.

Frequency is the number of complete cycles per second of a sound wave. Cycles per second abbreviated: cps or Hz.

Hz is frequency or cps.

Impedance is the complex ratio of the pressure difference effective in driving that portion of the volume velocity.

Specific acoustic impedance (Z) equals resistance (P) divided by reactance (U).

Acoustic impedance shows that the pressure differences across an acoustic element are analagous to voltage across the corresponding part of an electrical circuit.

Voltage is a measure of electrical pressure, abbrviated v.

Coupling is the transfer of power in any form, electrical or acoustical, from one part to the next.

Inductance is the property which opposes any change in existing current within a circuit. Inductance is present only when the current is changing.

Acoustic inertance is the combination in a single enclosure of acoustic capacitance and inductance. (Mechanical inductance).

Cutoff frequency is the frequency at which cancellation starts to occur.

Need for the Study

The consistently high volume of stereo cabinet construction that takes place each year at North Texas State University suggests that a comprehensive outline of the design and functions of hi-fidelity cabinetry could be most useful as a teaching aid for the woodworking instructor and a valuable guide for the student builder. There is also a need to take the highly technical information and language of hi-fidelity acoustics and synthesize it into a readable guide for enclosure construction.

Recent and Related Studies

There were many studies undertaken in book form that touched the subject of enclosure design but only a few that directly involved this study. In a study by Cohen (5), entitled *Hi-Fi Loudspeakers and Enclosures* , an explanation of acoustics and electronics of speaker enclosure designs was presented. Blitz (2) did a study on the elements of wave form theory and of wave propagation in relation to acoustical coupling. In a technical publication of James B. Lansing Sound Inc. (9), construction tips concerning choice of materials, assembly techniques, and damping techniques, served to point out the technical considerations necessary for enclosure design and construction. In a signed article by Victor Brociner (4) appearing in *Audio* magazine, the subject of improving bass response by various size-enclosure combinations was discussed. Many of the recent and related studies covered one small aspect of hi-fidelity sound reproduction, but very few attempted to cover the entire enclosure design and construction field.

Method of Procedure

Data were obtained from several sources. For the initial analysis of loudspeaker theory and sound theory, data were secured from books, technical publications, journals, periodicals, and current literature which gave insight to the subject. For the portion of the study dealing with construction techniques, personal interviews with builders and physics theoreticians were conducted to supplement the current publication material.

Organization of the Study

Chapter I involves itself with the basic structure of this study, including an introduction, purposes of the study, basic assumptions, limitations, definition of terms, need for the study, recent and related studies, method of procedure, and the organization.

Chapter II delineates the individual component parts of the loudspeaker and describes their functional relationship to the assembled speaker. Mechanics of loudspeaker design is dealt with in order to learn some of the criteria used to judge loudspeakers. Acoustic wave theory is discussed to clarify acoustic relationships between the speaker and the various enclosure types covered in the paper.

Chapter III is devoted to the most basic loudspeaker baffles and to their functional limitations. Formulae determining enclosure design is discussed in an attempt to show the individual characteristics of the infinite baffle group of enclosures. The popular acoustic suspension principle is covered in theory and accompanied by appendix tables to be used in computing various speaker/enclosure combinations.

Chapter IV deals with the Helmholtz theory as it relates to the phase inverter principle of acoustic enclosure design. Formulae and appendix tables are presented to aid the custom builder in correctly matching enclosure to loudspeaker. Detailed instructions are presented to cover the correct damping and tuning adjustments of phase inverter speaker/enclosure systems. Construction details specific to bass reflex enclosure systems are mentioned.

Chapter V involves itself with the operational theory of horn type enclosures. Wave propagation and design criteria for horn structures are discussed to show the complexity of undertaking a horn type system as a custom building project. Construction techniques necessary to an understanding of horn enclosures are presented, along with some construction details.

Chapter VI establishes general rules to be followed during the process of custom enclosure construction. Enclosure construction details covering use of materials, cabinet joinery techniques, mounting and wiring of speakers, and listening test procedures are discussed in this chapter.

Chapter VII presents the summary of the study, including findings, conclusions, and recommendations.

Appendices display tables, illustrations, and information sources helpful in the design and construction of custom built speaker enclosure systems.

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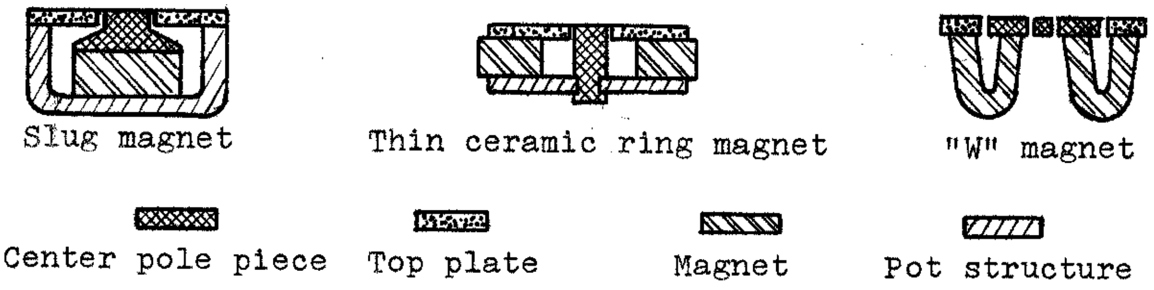
CHAPTER II

THE LOUDSPEAKER

On February 14, 1876, Alexander Graham Bell invented the telephone, and the field of acoustic reproduction became a wide-open field for experimentation and technological advance (6, p. 31). Using ideas from Bell's invention and data gathered from the experiments of early scientists such as Hans Christian Oersted and Michael Faraday, Peter Jensen and Edwin L. Pridham in 1913 invented the moving coil dynamic loudspeaker (11, p. 5). Many types of loudspeakers using different principles of sound reproduction have been developed in subsequent years. Electro-dynamic loudspeakers, electrostatic loudspeakers, crystal loudspeakers, and ionic loudspeakers are some types of transducers in use today, but direct radiator moving coil dynamic loudspeakers are by far the most commercially available and widely used. The permanent magnet dynamic loudspeaker has become universally popular because of its simplicity and flexibility of design. Reliability and ease of coordination with other equipment have made the permanent magnet dynamic loudspeaker preferred for such wide-ranging applications from transistor pocket radios to massive auditorium monitor systems.

Magnetic Assembly

There is a number of basic components common to all moving coil dynamic loudspeakers, but since the magnetic assembly has so much influence upon the amount and quality of the sound reproduced, it must be considered the heart of the loudspeaker. All loudspeaker magnetic assemblies have the same essential parts: a set of concentric pole pieces, a magnet, and a surrounding iron pot to carry the magnetism from the magnet to the pole pieces. The shape of the magnet may take the form of a slug, cored slug, "W", or other shapes. In most better quality loudspeakers the "W" shape is preferred (1). Earlier loudspeakers of the electrodynamic type used a direct current fed coil around the magnet to energize the assemblies; however, since the advent of the permanent magnet dynamic loudspeaker, use of the electrodynamic has diminished. Magnets most commonly used for loudspeakers today are ceramic or Alnico, with the permanent Alnico being preferred in more expensive loudspeakers. Figure 1 shows a sectional view of some commonly used types of magnet assemblies.


Slug magnet

Thin ceramic ring magnet

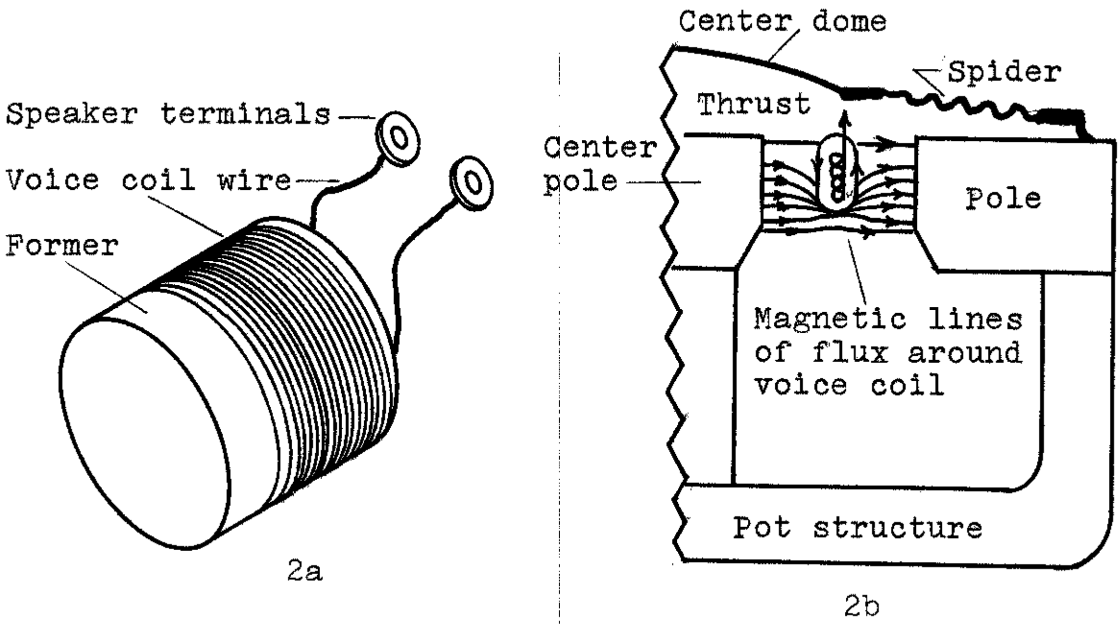
"W" magnet

Fig. 1--Typical loudspeaker magnet shapes

The most critical element in the design of a magnet assembly is the voice coil gap. To complete the magnetic circuit, magnetic energy must jump across the gap between pole pieces. The strength of the magnetic field in the voice coil gap varies inversely with the size of this precision-machined air gap. As the gap flux density becomes stronger, a more efficient motor action of the voice coil operating within the magnet assembly will be realized.

The Voice Coil

The voice coil is constructed by winding a predetermined number of turns of wire around a cardboard cylinder or bobbin. The wire used may be insulated copper or thin aluminum ribbon wound on edge. The entire coil is then held together with some type of binding cement such as epoxy resin. In a large speaker the voice coil will be approximately two inches long. Its leads are usually cemented to the middle portion of the cone or diaphragm surface and then brought to the outside of the magnet housing and attached to speaker terminals. The voice coil remains suspended within the gap between the two magnet pole pieces. The voice coil moves axially in or out of the magnet as a result of a signal current from the amplifier setting up a field within the coil that interacts with the permanent magnet field. Clearance between the voice coil and magnet poles is very small. An extremely large woofer of thirty inches diameter will have approximately ten thousandths inch clearance while a very small cone tweeter might have a clearance of three thousandths inch (5, p. 22). The amount of push exerted upon a voice coil and speaker cone in response to an input signal current depends not only upon the flux density within the voice coil gap, but also the amount of voice coil wire that is immersed in the voice coil gap at any one time. Figure 2a shows the voice coil and former as a unit and figure 2b shows the action of the voice coil in the magnetic gap.



2a

2b

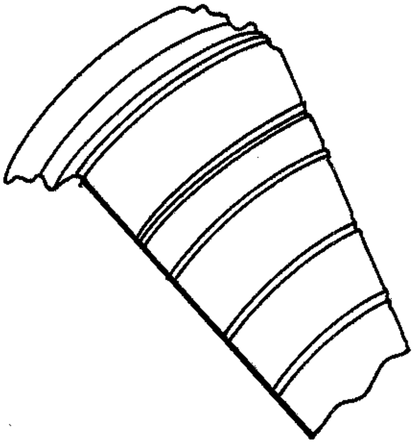
Fig. 2a and Fig. 2b--Voice coil gap

Manufacturers have many reasons for employing different combinations of magnet weight, shape, amount and kind of wire in the voice coil turns, and gap flux; but generally they try to use a deep gap to accommodate as many turns of wire as possible for a strong thrust.

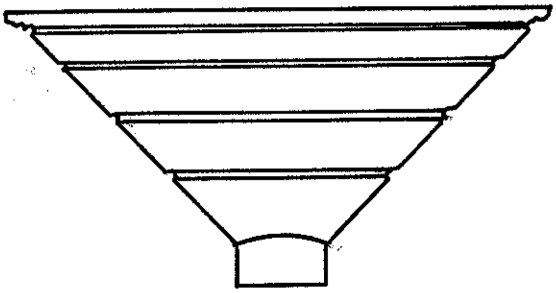
The Diaphragm

The leads from the voice coil and the bobbin are attached to the diaphragm or cone constructed of paper, cloth, or aluminum. As the voice coil reacts to an input signal by repelling itself in and out of the magnet voice coil gap, the mechanical energy introduced to the attached diaphragm is translated into acoustic energy. The diaphragm vibrates at a certain frequency, and an audible tone is generated. This energy conversion should provide the greatest amount of acoustic power output for a given amount of electrical input, with a minimum of distortion. The diaphragm must be made to follow exactly the dictates of the amplifier's output signal. Beranek (2, p. 184) states that "Current through the voice coil creates a magnetomotive force which interacts with the air gap flux of the permanent magnet and causes a translatory movement of the voice coil and, hence, of the cone to which it is attached."

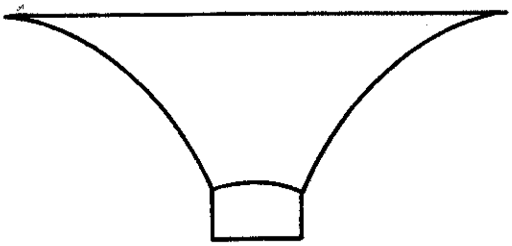
As the stiffness or mass of the cone is increased, the loudspeaker can produce a lower frequency. As the frequency is increased, sometimes a cone that is too light may break up into uneven nodal patterns or separate resonating frequency areas (2, p. 199; 8, p. 250). To insure proper decoupling of the multiple frequencies a loudspeaker is expected to reproduce, annular corrugated rings are molded into the cone so that the larger, stiffer sections may develop low frequency waves while the smaller, outer sections of the cone have only to reproduce the upper middle and high frequencies. Figure 3a shows a portion of a diaphragm while Figure 3b shows two different shapes used for cones.



3a



3b



3b

Fig. 3a and Fig. 3b--Conventional diaphragm shapes

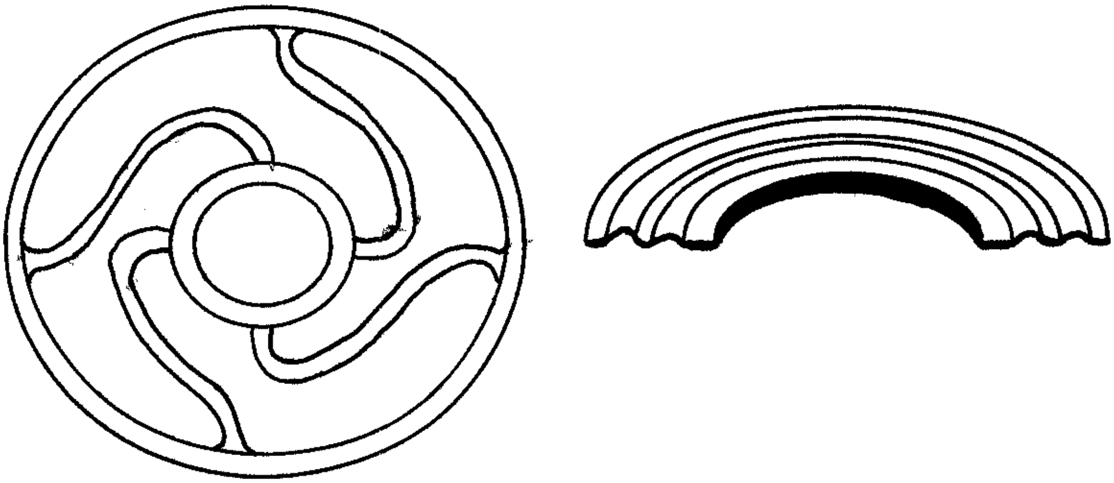
This design is most applicable for extended range dynamic loudspeakers.

It is nearly impossible for a single diaphragm to faithfully reproduce all frequencies from twenty cycles per second to twenty thousand cycles per second. The wave length of top "C" on a piano is three and one quarter inches while the wave length of bottom "C" on the piano is thirty-five feet. The most logical solution to this problem of obtaining adequate loudspeaker range would be to design a loudspeaker with a diaphragm large and stiff enough, with massive magnetic flux density, and a large voice coil capable of producing the lower frequencies only up to a point of about 1000 cycles per second. At the same time, a smaller speaker could be designed to reproduce the frequencies from about 800 cycles per second upward. This smaller speaker would not be capable of reproducing the lower frequencies of the larger one. The small speaker, called a tweeter, would not have a voice coil heavy enough to dissipate the heat generated by low frequencies, neither would it have a cone excursion long enough to accurately follow their wave forms. These two loudspeakers could be installed in tandem,utilizing a crossover unit to channel the frequencies below about 800 cycles per second to the larger woofer and the frequencies above that point to the smaller tweeter. This arrangement is approximately how a two-way speaker system operates. High fidelity loudspeakers have specific functions and are designed for specific applications.

Loudspeaker Suspension

The voice coil must be kept perfectly aligned mechanically within the magnetic gap during its vibration cycle. If the vibrations are non-linear, the voice coil may scrape against the magnet's walls, causing distortion and eventually, shorted turns in a burned-out voice coil. The voice coil is aligned in the magnetic gap by a centering device called a spider.

Early centering spiders were flat bakelite discs with openings resembling spider's legs. Modern voice coil centering spiders are usually corrugated cloth discs impregnated and sealed with a resin to keep foreign matter out of the magnetic air gap (5, p. 22). Figure 4 shows two types of spiders that have been used for loudspeakers.



Stamped bakelite

Corrugated flexible molded impregnated cloth

Fig. 4--Spiders

Since it is imperative that the voice coil move axially to the magnetic gap, the primary function of the spider is to help insure linear movement of the coil and attached diaphragm. Its second function is to help provide uniform mechanical resistance and some elastic restoring force to the excursions of the voice coil (12). Loudspeaker distortion at low frequencies is directly related to large voice coil excursions. To achieve constant power output over the bass range, cone excursions must quadruple with each lower octave.

Rim Suspension

Just as the spider supports and aligns the diaphragm at the center, the outer rim of the cone must be suspended by a surround to help achieve linearity of excursion and uniform stretchability without undue stiffness at the extreme of each cycle. The type edge compliance used for the surround is an important clue to the overall characteristics and application of the finished loudspeaker. A stiffly suspended loudspeaker (low compliance) will usually have several corrugated folds molded into its edge surround near the point where it is attached to the frame. While maintaining good linearity of cone excursion, low compliance surrounds allow relatively small cone travel at low frequencies. A loosely suspended loudspeaker (high compliance) will employ the use of a half-roll rubberized cloth cemented between the outer edge of the diaphragm and the rigid frame to allow unusually long cone excursions (7, p. 141). Figure 5 shows a composite of two types of rim suspensions and their proximity to the supporting basket.

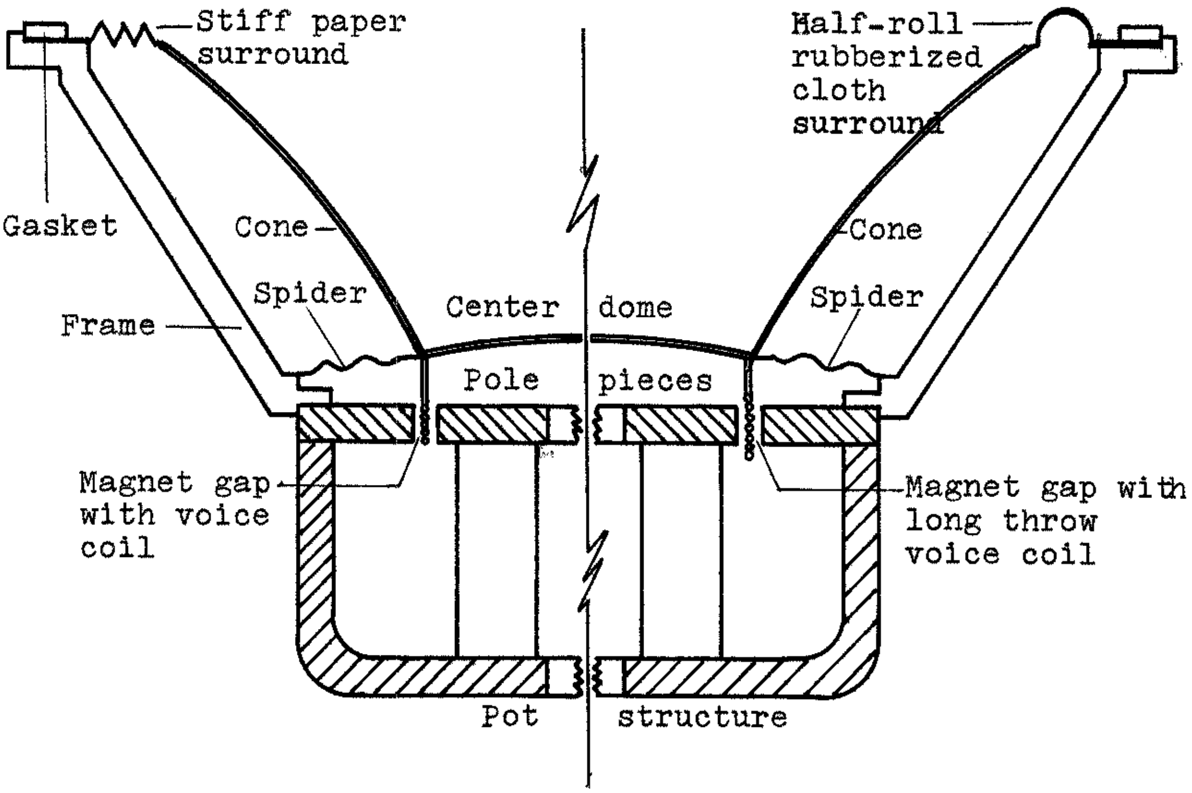


Fig. 5--Composite low and high compliance suspensions

The Frame

Various elements of the loudspeaker are supported by a housing or basket structure. Depending upon the size, weight, and application of the loudspeaker, this frame may be either cast metal or stamped sheet metal. It must be absolutely rigid in order to support the entire structure and not deform when screwed down tight to a baffle board. Any mechanical weakness may result in severe damage to the loudspeaker.

Mechanics of Design

In most modern acoustical work the sound pressure waves are picked up by some electroacoustical transducer such as a microphone,and after proceding through an amplifier are converted back into sound vibrations by a transmitting electroacoustic device such as a loudspeaker. The modern hi-fidelity loudspeaker is called upon to perform the task of reproducing very large ranges in frequency and volume. The design parameters of a loudspeaker involve such factors as frequency response, efficiency, low distortion, tenacity of cone excursion,power handling capacity, transient response,and cost (8, p. 247).

There are tremendous physical stresses placed on the modern hi-fidelity loudspeaker. As the loudspeaker converts one form of energy (electrical) to another (acoustical), it must be linear, passive, and reversible in nature. In a general sense, linearity means that the loudspeaker will impart acoustically the electrical signals sent it by the amplifier without adding coloration of its own. Reversibility means the loudspeaker is capable of transmitting a signal much as a microphone. Passivity means the loudspeaker, although it has potential energy stored within the permanent magnet, reacts only when excited by a current through its coil. The moving coil dynamic loudspeaker is primarily mechanical in nature. Kinsler and Frey (8, p. 247) stated that an ideal modern dynamic loudspeaker:

> (1) would have an electroacoustic efficiency approaching 100 per cent.
> (2) would have an acoustic output response that is independent of a frequency over the entire audible range.

(3) would introduce neither harmonic nor intermodulation distortion into its output.

(4) would faithfully reproduce transients as well as steady input signals.

(5) would be capable of producing a non-directional radiation pattern.

(6) would be of as small a size as possible depending upon the required acoustic output.

At the present state of the art, a transducer has not yet been developed capable of fulfilling these criteria, but they do represent a good reference point from which we can analyze the working of a loudspeaker.

Acoustic Theory

Sound is perceived as a wave motion in which particles do not move with the waves but vibrate only about their mean positions. The widely accepted particle velocity theory is that, upon the generation of a sound, the particles move away from the source, striking and displacing each successive particle in the sound's path. Under these conditions only the energy of sound is actually traveling away from the source, not a blast of air carrying the sound. In the wave motion there is the alternate compression and rarefaction of the air, much as a cork is moved along the crest of a wave while the water remains in a relatively general position (3, p. 15). Figure 6 shows the action of wave motion into a listening area of a baffled loudspeaker.

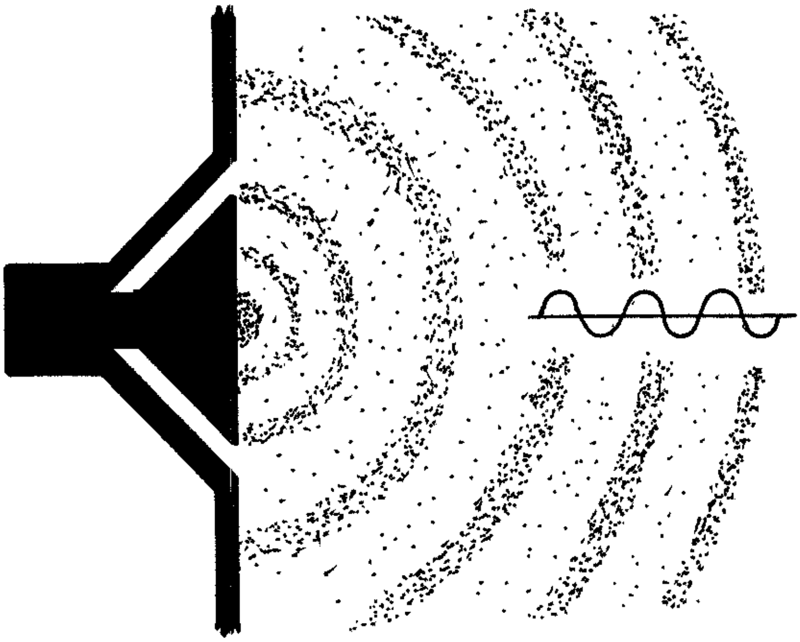


Fig. 6--Motion of sound waves in air

When the signal from the amplifier through the loudspeaker voice coil cuts across the magnet gap flux, this causes the diaphragm to travel back and forth setting in motion the radiation of sound energy. As the frequency is lowered, the wave length is increased. Wave length may be determined by the formula (7, p. 19):

$$\lambda_{\text{feet}} = \frac{\text{1128 feet per second}}{\text{frequency}} \text{ (speed of sound)}$$

Since high frequency speakers have less of an enclosure matching problem, and because of the very short wave lengths they emit, this paper will be primarily concerned with the problems of understanding and dealing with the low frequency transducers. Rated cone diameter is the advertized size of the loudspeaker. Woofers can be as small as three inches or, in the case of one commercial manufacturer, thirty inches. Just as a large bass drum displaces more acoustical power than a tambourine, a practical limit on the minimum cone diameter will be placed on the hi-fidelity woofer. The three most common size woffers stocked in hi-fidelity stores are the eight-inch , twelve-inch, and fifteen-inch low frequency driver. A loudspeaker with a rated cone diameter of less than eight inches is capable of producing low frequencies but generally with such low acoustic power as to render it unsatisfactory for quality reproduction. Except in very special applications, a woofer with a rated cone diameter larger than fifteen inches will have difficulty in correctly following the wave forms. At frequencies below approximately 500 cycles per second, the time displacement of sound is great enough so that the cone will not break up into nodal frequency patterns but moves as a unit in mass-stiffness system.

Loudspeaker Efficiency

Efficiency of a loudspeaker is expressed as a ratio of acoustic power output to electrical input (9). Electrical efficiency depends upon power lost in the voice coil turns. Magnetic efficiency depends upon the voice coil's interaction with the flux density within the magnetic gap. Mechanical efficiency depends upon the rigidity of the piston suspension characteristics of the spider and surround. Radiation efficiency depends upon the ratio of piston diameter to frequency of radiation (5, p. 109). Efficiency is by no means a criterion for judging quality. There are good quality high-efficiency speakers and good quality low-efficiency speakers. Each type of loudspeaker has its own application, and the manufacturers of both types of loudspeaker present convincing data as to why their type is more desirable. Efficiency is a by-product of all the factors mentioned above, but the term has become synonomous with two different schools of thought in the loudspeaker system manufacturing industry. It is therefore necessary to explain some of the reasoning behind these design approaches so coveted by different loudspeaker manufacturers.

A low-compliance loudspeaker has a voice coil that just about matches the length of the magnetic gap. If the speaker could be driven so hard as to make the voice coil leave the gap, there would be a momentary loss of amplifier energy. A low-compliance loudspeaker, limited in elasticity of cone excursion to a maximum of about three-sixteenth inch, will need some help in acoustic loading at lower frequencies; but it will always have the driving force of an energized voice coil. The loudspeaker will therefore be relatively efficient by virtue of the fact that it loses little electrical input to unused portions of the voice coil. The proponents of high-efficiency systems declare that, properly loaded, the small cone excursions will result in less distortion, and the system will be capable of true realism at concert levels. They make the point that nearly all theaters and recording studios around the world use high-efficiency, low-compliance monitor systems.

Since the basic problem in reproducting the lower frequencies is that of the diaphragm grabbing hold of enough air, another approach taken by manufacturers is to design a speaker cone with a high compliance capable of abnormally long excursions. It can couple with the air at extremely low frequencies to produce the lowest fundamentals, some below audibility. Of course, a voice coil of greater length would be necessary for this loudspeaker application; otherwise it would spend most of the time outside the magnetic gap during elongated cone excursions which may extend to as much as three-quarters of an inch (t, p. 110). This type of overhanging voice coil is called a long-throw coil. The overhanging voice coil has the advantage of always having energized turns of the coil within the magnetic gap. At the same time, it has a disadvantage because portions of the coil not actually in the gap must still be energized to complete the electrical circuit. The overhanging portions of the voice coil represent wasted electrical amplifier input because the unused voice coil turns are not doing any work. Figure 7 shows the different length voice coils used in high-compliance and low-compliance speakers and their action when driven to concert levels.

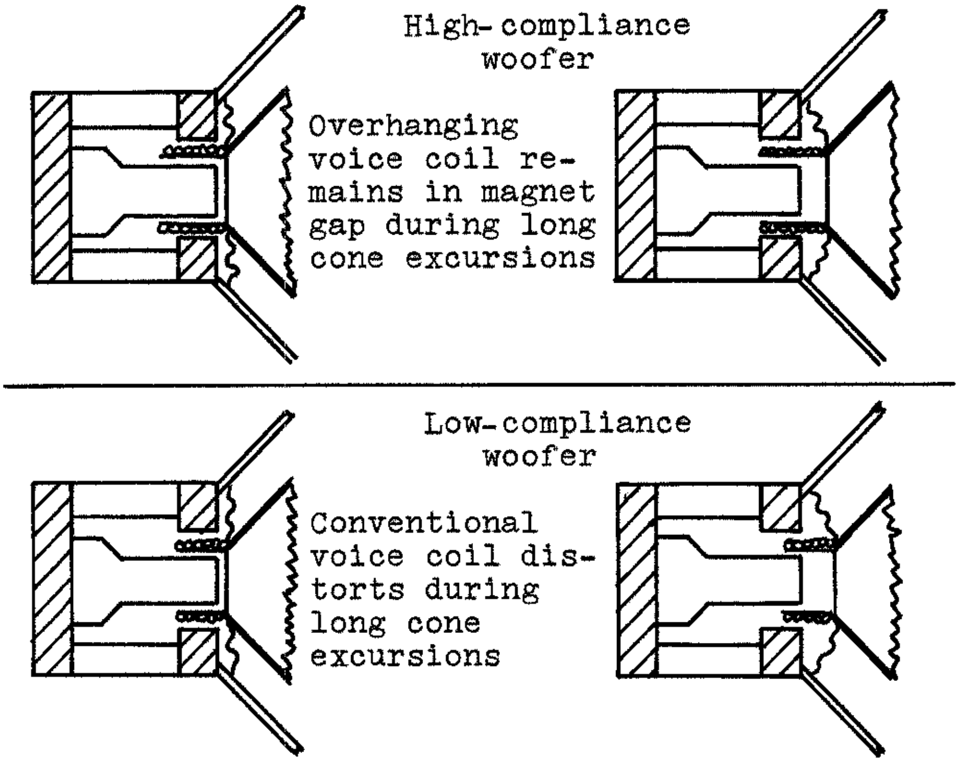


Fig. 7--Conventional vs. Long-throw voice coil

High-compliance, low-efficiency loudspeakers require more powerful amplifiers to drive them. High power, low distortion transistor amplifiers are readily available on the market, assuming, of course, their higher cost.

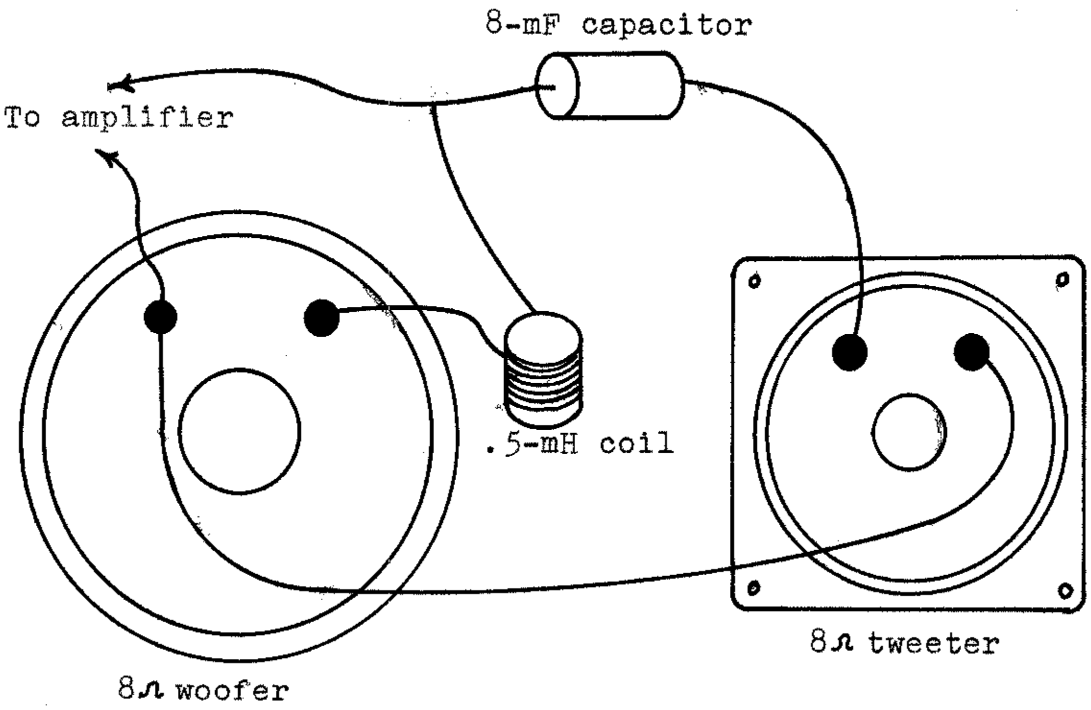
Loudspeaker Impedance

The voice coil winding exhibits a resistance of the wire used in the turns, an inductance, and a small amount of capacitance distributed between turns. This resulting self-impedance in combination with the reflected acoustic impedance of the enclosure makes up the impedance characteristic the loudspeaker system will present to the amplifier (4, p. 191).

The rated impedance of a loudspeaker is usually taken in the 400-cycle range, and may be easily ascertained by measuring its d-c resistance with a simple ohmmeter and increasing that value by 15 to 20 per cent (5, p. 97). A loudspeaker's highest impedance occurs at the frequency of its natural resonance. If this resonant peak is not sufficiently damped, there will be a bump in the response curve and an undesirable boominess at a certain frequency. One way of smoothing out this undesirable resonance is to use an amplifier with a very low source impedance at its output stages. In addition to this, a correctly designed and constructed speaker/enclosure combination will help provide the proper damping and smooth out jagged resonant peaks in the response curve. The type enclosure or housing, as well as internal fillers within the enclosure, plays a most vital role in the performance of the finished loudspeaker/enclosure system.

Crossover Networks

Because loudspeakers are designed to do a particular job, manufacturers of high quality systems seldom use only one extended range driver to reproduce the entire audio spectrum. Most hi-fidelity systems employ a two- or three-way woofer-tweeter combination. The function of the electrical dividing network, usually called crossovers, is to make sure only the appropriate frequencies of the audio spectrum are fed to the individual units in the system. Failure of a crossover to perform its job correctly may result in distortion of the output or damage due to overheating of the voice coils. A simple high-pass filter may be installed in series with the tweeter, but commercially available crossover units use an additional low-pass filter to direct only low frequencies to the woofer (10, p. 10-14). Figure 8 shows a simple woofer-tweeter two-way system with a high-pass filter blocking destructive low frequencies to the tweeter and coil or choke to keep unnecessary highs out of the woofer.



Crossover point=2500 Hz

Fig. 8--Simplified method of wiring two-way speaker system

Crossover design and custom winding are not within the scope of this paper, but for those who desire to build their own crossover networks, information may be obtained from manufacturers' technical publications and electronics manuals.

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CHAPTER III

FINITE, INFINITE AND ACOUSTIC SUSPENSION BAFFLE

A common fallacy concerning the design and function of a speaker enclosure is that it should resonate, and have tone as a musical instrument does to propagate the sound. Just as a speaker should have no particular coloration of its own, neither should the enclosure have tone coloration; serving only as a sturdy passive housing for the speaker relating only to its input signal (3, p. 7). A loudspeaker radiates from both sides of its diaphragm putting the sound waves 180 degrees out of phase. Figure 9 illustrates the wave destruction of an unbaffled speaker.

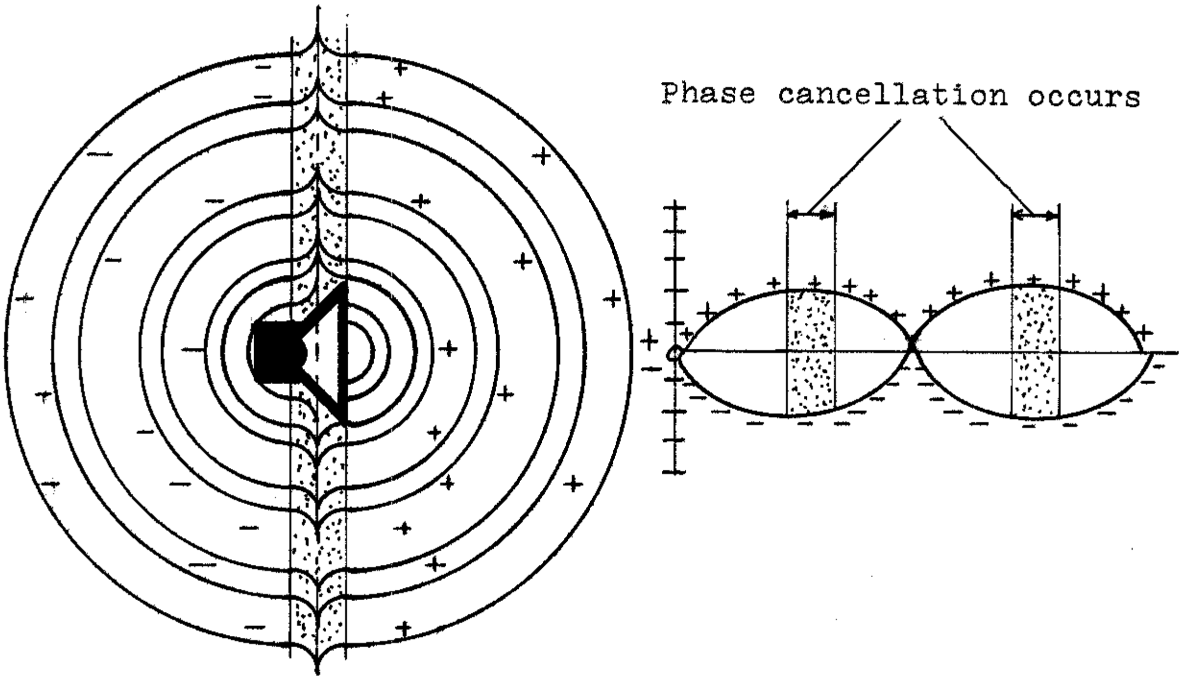

Fig. 9--Acoustic Doublet

As the cone responds to the initial input signal from the amplifier, it begins a forward thrust which creates a rarefaction at the rear of the cone (6, p. 199-200). This direct radiation air cancellation of an unbaffled speaker is called "doublet cancellation" or acoustic doublet (12, p. 78). The primary function of any enclosure or baffle is to isolate the radiation from the rear of the speaker so that it does not cancel the radiation generated from the front of the cone. A baffle should separate the front and rear of a speaker cone by at least one-half wave length the lowest desired frequency (11, p. 1). As the frequency decreases, the wave length increases. Low C on the piano has a frequency of 32.7 feet and a wave length of approximately 35 feet (10). It would, therefore, take a baffle of approximately 17 feet diameter to isolate the front and rear of the cone by one-half wave length (3, p. 9-10; 8, p. 144). The formula for finding the cutoff frequency is (9, p. 224):

$$\text{cutoff frequency } \lambda = \frac{V}{F}$$

λ = wave length in feet
V = velocity of sound in air (1128 ft./sec.)
F = frequency of sound in Hz.

Finite Baffle

One of the most common and least expensive ways to separate these speaker radiations is to mount the speaker in an open-backed box with a front wall area of about three feet square. Usually called finite baffles, they are most commonly found in packaged, furniture-type stereo console systems.

Appendix C shows a finite or open-backed box. These open-backed boxes were used in the early days of radio when the frequency requirement of a loudspeaker was much less demanding. The finite baffle can help make the speaker more directional. Some of the inherent internal wave cancellation can be reduced by locating the speaker slightly off-center of the mounting board (4, p. 210-211). The more obvious disadvantages of this type of baffle are its inability to effectively cancel the lower frequencies of a modern extended range loudspeaker and its lack of acoustic damping control of the free air resonance of the loudspeaker (6, p. 202). Because of these limitations of the open baffle, it is hardly ever used in modern hi-fi practice; but an understanding of its function will help reveal the techniques other enclosures employ to overcome defects of the finite baffle.

Infinite Baffles

An obvious extension of the open baffle attempt to prevent doublet cancellation would be the infinite baffle. An infinite baffle in its original concept is a very large wall, probably about 450 feet square, through which the speaker is mounted. The wall becomes an infinitely large baffle board isolating front to rear wave cancellation entirely (11, p. 1). This type of installation may be most common in public address systems where the speaker is mounted in the walls of an establishment. Infinite baffles may be used in the home to provide an economical and space saving installation. Speakers mounted in a wall of a home vent their rear radiation into an adjoining room. They take up little or no living space, may be strategically located on the walls for best stereo or quadraphonic spatial effect, and can be made to look inconspicuous. Closet doors, when reinforced and gasketed, make a good mounting board for the speaker. The absorption coefficient of the clothes in the closet help soften and absorb the pressure waves radiated from the rear of the speaker preventing doublet cancellation (5). This type of installation provides an easy access to the speaker components. Infinite baffles of this type must depend upon the quality of the loudspeaker to determine the final quality of the speaker system.

A major factor to be concerned with is the loudspeaker's ability to move enough air at low frequencies to achieve the listener's desired sound pressure level. In a quality system, baffled in this way, achieving adequate low frequency response would be very difficult unless fifteen-inch drivers were employed. Multiple speaker arrays might be required to obtain the desired cone area depending upon the low frequency capabilities of the loudspeaker. As with the open-backed baffle, the wall-mounted infinite baffle does not exert any control over the resonant peaks or deficiencies of the loudspeaker. This type of installation, because of its space-saving advantages, may utilize enough quality extended range speakers to achieve satisfactory sound reproduction at near concert levels.

Sealed Enclosures

A large, totally enclosed box may be used to baffle the loudspeaker. This type of enclosure is infinite only in the sense that it totally prevents rear radiation from reaching the listening area and the front side of the diaphragm. Large infinite baffle systems have the advantage of not wasting the rear cone radiation. These speaker systems are preferred by audiophiles who prefer their enclosures to be a piece of furniture and who do not wish to cut a large hole in their walls or closet doors.

The resistive load this totally enclosed volume of air presents to the speaker cone will have the tendency to change its resonant frequency. All other characteristics being equal, generally the heavier the mass of a diaphragm the lower its resonant frequency (9, p. 16). Response falls off at the rate of twelve db per octave below resonance, so the enclosure must be properly correlated with the speaker's suspension system to avoid highly restricted bass response (12, p. 72). Despite this increase in resonant frequency, the actual low frequency response will roll off more slowly than the open-backed or wall-mount baffles because of the elimination of acoustic doublet and the work load presented to the speaker. In a large no-compromise infinite baffle system such as the Bozak 310A of approximately sixteen cubic feet,or the Altec A10 theatre system, the multiple drivers chosen are of medium efficiency with heavy magnetic structures for good transient response (2; 3, p. 41). The actual size enclosure to be used in a custom built system is, in the final analysis, going to be determined by the amount of space available in the proposed listening room. Once the furniture considerations are established the speakers chosen should be determined by the following criteria:

1. Volume at which the system is to be driven will determine the cone area (number and size of drivers).
2. The damping factor of the amplifier to be used along with power output.
3. If a multiple array of drivers is chosen, will there be phase shift because of their mounting configuration, and will they present sufficient resistive load to the amplifier output terminals?

Many of these questions will be answered with the technical letter accompanying the loudspeaker in its shipping carton.

A system such as the Bozak 310A series which employs either two fifteen-inch drivers or four twelve-inch drivers when driven to studio monitor levels, will develop tremendous internal pressures and possibly result in strong, diffracted waves or standing waves. For this reason, speakers should be moved off-center of the baffle board by at least several inches, and opposite sides of the enclosure should be acoustically damped with two-inch thick insulation (4, p. 227-230). These strong internal waves radiating from the woofers could modulate the midrange and tweeter cones, altering their reproduction. For these reasons, any infinite baffle system designed to produce good bass response at concert listening levels employing the use of cone-type midrange and high-frequency drivers should, as a precaution, isolate these in their own separate housings. In the event a horn-type driver is to be used in the high frequency sections, the horn becomes its own housing because it is totally sealed.

The internal bracing of an enclosure of this size is most important. Any flexure of the walls results in wasted loudspeaker energy. An enclosure of fifteen cubic feet will probably have some side walls as large as six square feet and some back and front walls possibly as large as twelve square feet. The walls of this size enclosure should be a minimum of three-fourths inch thick plywood or flake board. Any solid cabinet maker's joint may be used to attach walls as long as they are glued and screwed together with glue blocks, furring or scabs at the wall intersections. The cabinet should be solidly braced horizontally or vertically with two-inch by four-inch pine stock on any wall surface having an area larger than fifteen by twenty inches (7, p. 10). The front baffle board will be weakened by the speaker cutout mounting holes. It is therefore most important that there be front to rear bracing with two-by-four stock at any point of weakness such as the area between two speaker cutout holes. A check for any vibrations can easily be made by playing a program with the good bass response through the system at very high levels. By placing hands over the outside walls of the enclosure, resonances can be felt to determine where bracing is needed.

These two relatively large infinite baffle systems use moderately efficient drivers in tandem to achieve desired bass response as the frequency decreases. Each speaker employs a large size cone for small excursion and good bass. These systems still have a disadvantage because of their physical size. There is also a problem of loading woofers at low frequencies since the radiation resistance will be the air in the room. To prevent the stiffness of the enclosure from raising the speaker's resonance by more than ten per cent, the enclosure volume should be at least 3.5 cubic feet for an eight-inch speaker, 8.5 cubic feet for a typical twelve-inch speaker and fifteen cubic feet for a fifteen-inch speaker (6, p. 209).

Acoustic Suspension Speaker System

It is safe to assume very few audiophiles would care to give up the amount of living area in their homes that a pair of fifteen cubic feet infinite baffle enclosures would require. With the increasing popularity of quadrasonic sound, the possibility of finding space for four of these enclosures becomes more remote. As the size of a closed box is reduced to dimensions where it is suitable for use in the average living room, the air trapped inside the enclosure presents a capacitive resistance or acoustic restraint upon the loudspeaker. As soon as the diaphragm moves foreward pushing out its initial wave, there is created a momentary vacuum behind the diaphragm. This effect of trying to influence the diaphragm to a neutral position is more pronounced with low frequency wave propogation. This enclosed air mass constitutes an added stiffness to the speaker cone suspension system which may drastically raise the resonant frequency of the speaker (12, p. 72). Altec claims that one of its low-compliance speakers with a free air resonance of fifty cycles may rise as high as eighty cycles when mounted in a small closed box (11, p. 2). This would certainly be an unsatisfactory arrangement because the low-compliance loudspeaker would not have a long enough cone excursion to couple with lower frequencies. A high-compliance loudspeaker capable of extremely long voice coil excursions would be capable of coupling the air mass of the longer wave lengths.

Acoustic suspension speaker systems were pioneered in 1954 by Acoustic Research Incorporated. They designed a very low-resonance speaker with a heavy mass diaphragm that was loosely suspended from the frame by a soft, pliable material. Since the air entrapped within their enclosures of about two cubic feet presented an almost perfect acoustic spring to the diaphragm, they designed uniform stretchability in the surround and spider so that all three elements could work together for linearity of cone excursion. Acoustic Research is deeply committed to the air suspension design claiming its four distinct advantages are as follows (1):

1. Very low distortion at lower frequencies through acoustic rather than mechanical suspension.
2. Extended bass response through extended cone excursion, essentially to the lower limits of human hearing.
3. Conveniently small size because of the need for a small volume of air behind the speaker cone.
4. Simplicity of design and lower cost.

Figure 10 illustrates the pneumatic restraint the air within the totally sealed acoustic suspension enclosure imposes upon diaphragm excursions.

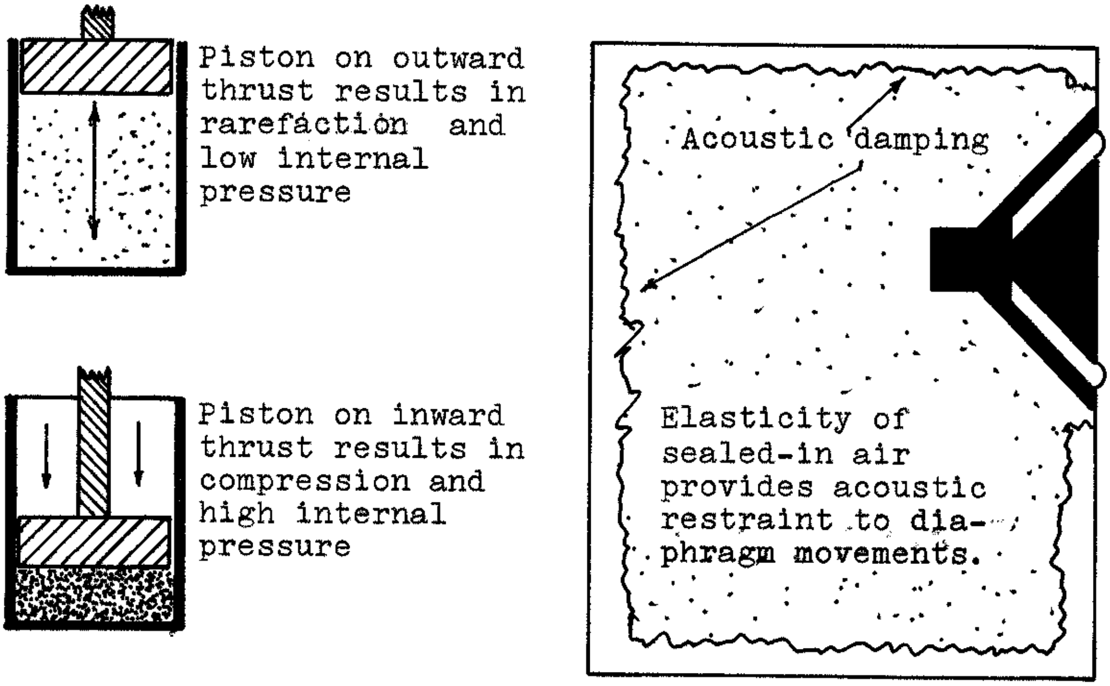

Fig. 10--Acoustic suspension-theory of operation

Because of a number of reasons, primarily their small cabinet size to the apartment dwellers, Acoustic Research has developed and marketed the air suspension principle to a position of being one of the most popular speaker systems sold today.

Efficiency Considerations

The combination of heavier cone mass, extended cone travel, and air cushion may bring the efficiency of an acoustic suspension speaker system to below one per cent. For this reason, an amplifier with a good damping factor, ninety or above, and a power output minimum of twenty watts per channel, will be necessary for moderate listening levels with low distortion.

Construction Details

These "bookshelf" speakers as they are sometimes called will probably have baffle panels or walls not larger than two and one-half square feet. If they are constructed of three quarter inch thick material, a minimum of bracing will be necessary; however, the adjoining walls should be glued and screwed together with rails or glue scabs to insure a good air seal. Failure to correctly seal an enclosure of this size would almost certainly result in audible air leaks or squeals at low frequencies.

Despite the fact that the infinite type baffles do give better overall response than an open baffle, they all suffer some disadvantages. All infinite type baffles, if underdamped, may develop a single note resonance or boominess. The basic problem encountered by a speaker mounted in an infinite baffle is that of grabbing hold of enough air at lower frequencies to have a useful work load. As frequency decreases, it becomes more difficult for the loudspeaker to maintain this resistive work load. The remedies taken by all infinite baffle systems are to use either a larger diaphragm, two or more diaphragms, or a diaphragm with a very long stroke or excursion. One way to overcome this important problem would be to have a speaker enclosure that would automatically present an increased work load to the loudspeaker diaphragm as the frequency decreases. That is exactly how the bass reflex enclosure operates, as indicated in Appendix D (9, p. 57).

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CHAPTER IV

PHASE INVERTER OR BASS REFLEX ENCLOSURE

This bass reflex principle, developed by Albert Thuras of Bell Laboratories, has a patent date of August 15, 1930. The principles upon which this type of enclosure were developed all stem from the work of a well known pioneer in acoustics, Hermann von Helmholtz. His work was done in the late nineteenth century as part of the research into the sensations of hearing; but most of the data are directly applicable to the resonance characteristics of ported loudspeaker enclosures (10, p. 82).

The bass reflex enclosure is essentially like the closed box of the infinite baffle except that it has a port opening usually located on the front baffle mounting board. The volume inside the box represents an acoustical capacitance to the rear motion of the diaphragm. The port opening represents an acoustic inductance. This combination of capacitance and inductance within an acoustic circuit is called acoustic inertance. As both the volume of the box (capacitance) and the port opening (inductance) can be made variable, the bass reflex enclosure becomes a tunable circuit. This enables the builder to tune the enclosure to the loudspeaker, achieving a truly matched speaker system.

Cabinet resonance may be determined by the Helmholtz resonator equation (2, p. 229): $f = 2070 \sqrt[4]{\frac{A}{V}}$ where,

f = resonant frequency of the cabinet in Hz

A = area of the port in square inches

V = volume of the cabinet in cubic inches

There is another important aspect of the bass reflex enclosure. The unused rear wave energy trapped in the totally enclosed baffle can be made to do useful work. The sound wave eminating from the rear of the speaker diaphragm must travel some distance before it may emerge from the port opening. Although the stiffness of the air is not as great as that in the acoustic suspension baffle, there is still a good amount of air mass stiffness developed by the capacitance of the air in the enclosure moving through the acoustic resistance of the port opening. If, in the process, the distance the rear wave must travel will shift it 180 degrees out of phase with the front wave, the rear wave will then be in phase with the front radiated sound. This action, called the phase inverter principle, imparts three important benefits to the loudspeaker:

1. It prevents destructive doublet cancellation.
2. It makes the sound from the rear of the speaker perform a cumulative effect with the front sound thereby providing a second source of energy.
3. It has the function of making the loudspeaker work harder as the frequency decreases.

Figure 11 illustrates the phase inverter principle by which sound from the rear of the diaphragm can be made to do useful work.

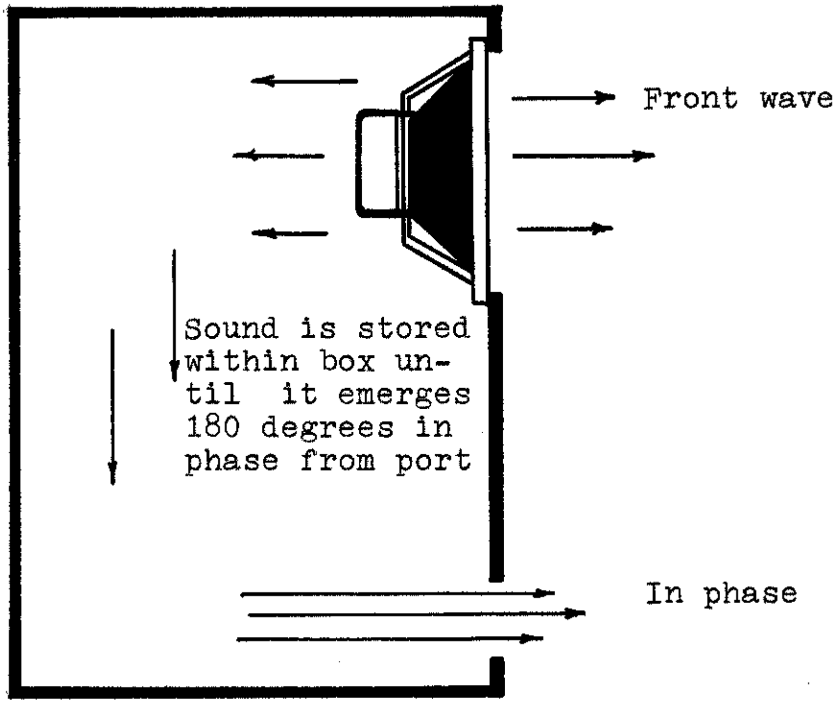

Fig. 11--Phase inverter

This acoustic loading causes the diaphragm to move no farther at forty cycles per second than it does at two hundred cycles per second (8, p. 2-3). Since the cabinet must store up acoustic energy before it can release energy out the port, the phase inversion principle works only at lower frequencies. At middle and upper frequencies the enclosure operates essentially as a closed box. When the enclosure is tuned at or slightly below the resonant frequency, an interesting thing happens. The system no longer displays a single resonant peak, but instead has two resonant peaks of lower amplitude straddling the original resonant point. These two peaks extend the resonant points to about an octave above and below the single resonance point. This results in a damping of the resonant boominess by extending the response fairly smoothly over a broader spectrum.

Determining Port Size

The size of the port area has a definite relationship to enclosure volume. For a given size enclosure, the resonant frequency increases as the port opening decreases. For a given size port opening, resonant frequency increases as the volume of the box decreases. The fact that these parameters may be juggled to obtain desired performance means the enclosure size may be built adaptable to the furniture requirements for any living area. Simply cutting a hole in the baffle board will not insure proper damping of the system. If the port is located too close to the speaker cutout, the path from the rear of the cone becomes too direct and acoustic doublet cancellation may occur. Another essential step in equalizing the "bumps" in frequency is to cover the opposing inner walls with a soft, acoustically absorbant lining such as fiberglass. If additional equilization is required, grille cloth may be stretched across the port opening to provide more acoustic resistance to the rear wave fronts. The nomogram in Appendix D shows the optimum size relationship of enclosure volume and port area for a given diameter loudspeaker. While these figures represent nominal parameters, they are by no means intended to give optimum tuning under all conditions. A 10 per cent variation in cabinet volume or port area will probably have little effect on the system's overall quality.

Tuning the Enclosure Port

A more accurate tuning of the loudspeaker's resonant peak may be achieved by a simple method requiring an inexpensive audio oscillator, a volt meter, and a resistor having a value of between ten and fifty times the rated impedance of the loudspeaker. Figure 12 shows the correct setup for determining the resonant peak (1, p. 77).

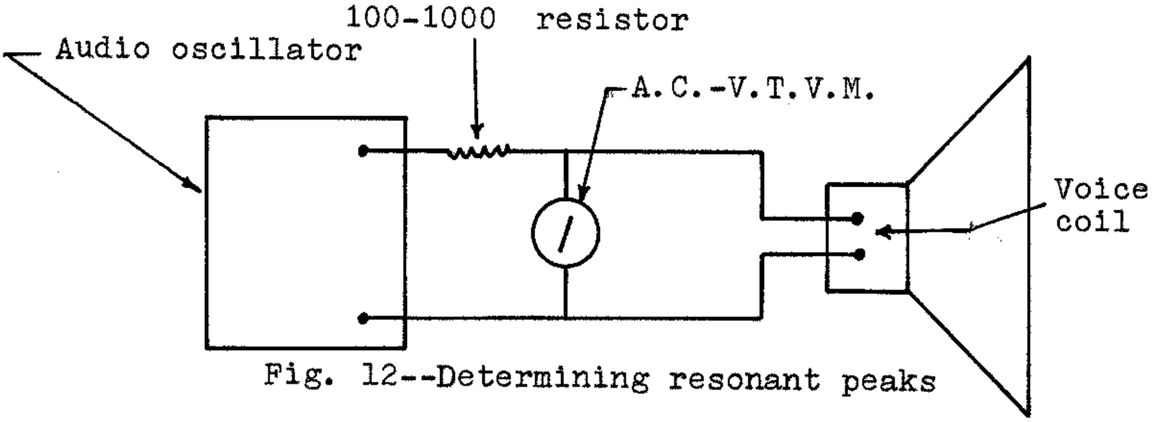

Fig. 12--Determining resonant peaks

As the audio oscillator is slowly swept through the low frequency range, about 20Hz-200Hz, the voltage reading will vary in direct relation to the impedance of the mounted loudspeaker and its enclosure (5, p. 148). At resonance there will be a noticeable rise in voltage. Once this resonance is determined, the proper port area may be chosen from the nomogram in Appendix D. With the proper damping of interior walls and the correctly chosen port opening, the single resonant peak should be replaced by two equally spaced voltage peaks of equal amplitude, one on either side of the loudspeaker's resonant frequency. These two peaks will probably be about an octave above and below the single resonant point. Figure 13 shows the original resonant peak and the twin peaks of lower amplitude as a result of proper tuning and damping the enclosure (3, p. 218).

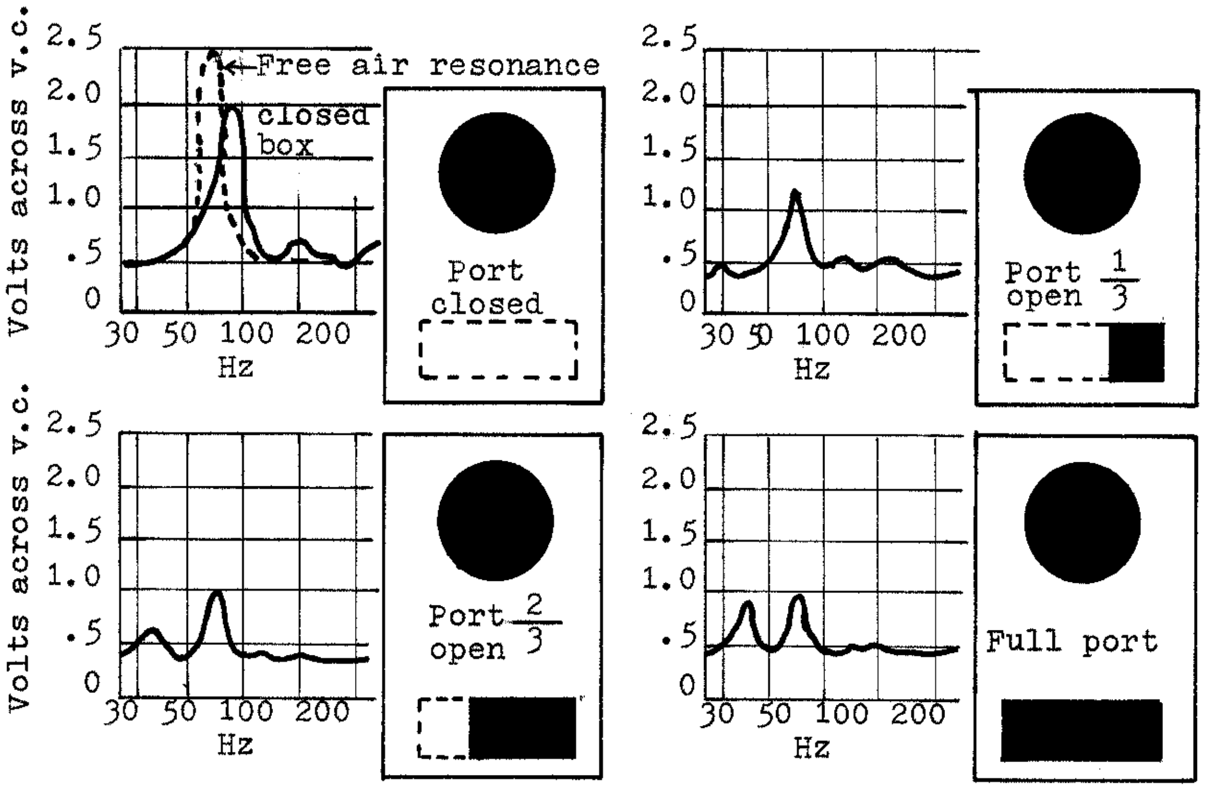

Fig. 13--Examples of port tuning

If the two peaks are of different amplitudes, improved results may be obtained by increasing or decreasing the area of the vent until the desired results are obtained.

Ducted Port

Bass reflex enclosures are the most flexible of all enclosure types because their size is adaptable to many different loudspeakers. Their tuning capability of the port area just about insures a good loudspeaker/enclosure match. There is a point, however, when the volume of the cabinet becomes too small to be compensated by port tuning and the result is a noticeable drop in bass output. This can be overcome by extending the vent aperture inward by means of a duct, tube, or dividing partition within the cabinet. This action will result in an elongated path for the rear wave causing it to lag acoustically before it can emerge into the listening area. With the addition of a ducted port, conventional bass reflex enclosure size may be reduced up to fifty per cent. This duct has the advantage of isolation-baffling the higher frequencies because they do not turn corners very well (1, p. 74). Referring to Appendix E,supplied by the technical service department of Jensen Manufacturing Company (6), it can be readily seen that the relationship of the volume to speaker resonance dictates the necessity of using a closed box, ported box, or ducted port. The flow of the chart indicates that as the internal volume decreases,the longer wave lengths require extended baffling. The diameter and length of duct recommended by Jensen is a series of code prefixes located directly below the chart. Listed volumes are exclusive of absorption material, bracing, or loudspeaker space.

Damping the Ducted Port

As the enclosure becomes smaller, the cutoff frequency rises and the result may be a hangover or boominess caused by under-damping. Optimum damping of transients is determined by the ratio of air mass stiffness within the enclosure to the stiffness of the speaker diaphragm (1, p. 76). An amplifier with a good damping factor will help reduce the decay time of transients within an enclosure. Acoustic resistance may be increased by tightly stretching a grille cloth or acoustically transparent mesh-like material across the port opening (2, p. 229).

A simplified technique for determining the correct damping of transients for a given enclosure/system is described by Jordan and Cunningham in their book The Sound of High Fidelity ". . . [with a] d.c. voltage for a 1.5V. flashlight battery applied to speaker poles . . . a click or ringing thump may be heard. By opening or closing the port, the noise may become a thump, or bong, or change to a click." (7, p. 115). Figure 14 illustrates a simple d.c. hookup for adjusting the damping in a ducted port system.

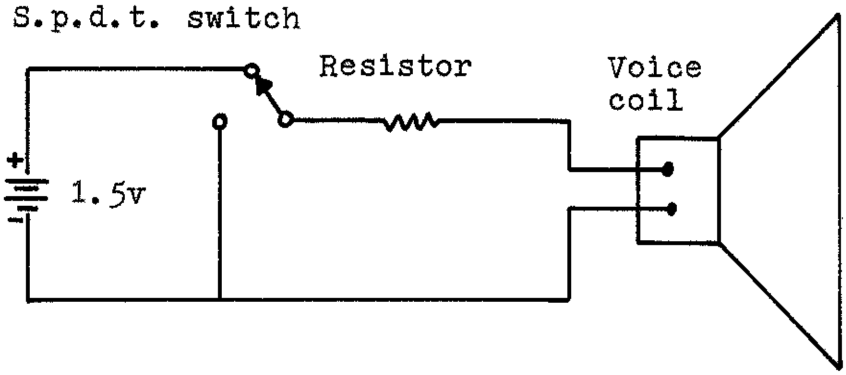

Fig. 14--Testing for damping Q

The repeated opening and closing of the circuit causes the diaphragm to pulse a low amplitude transient which can be reasonably damped by the builder of the enclosure. Speaker systems exhibit different characteristics in variously damped listening rooms. It is therefore possible to use this technique to critically tune the enclosure in the event it is moved to another listening area.

Construction Considerations

Since most bass reflex systems use high-efficiency, low frequency drivers, the internal volume of the enclosure will probably be more than four cubic feet. James B. Lansing (4) recommends internal bracing of any panel larger than fifteen by twenty inches. The cabinet must be well built and all joints should be true and tight. All large panels should have two inch by four inch bracing glued on edge and fastened securely with wood screws to prevent any vibrations. Appendix F indicates typical internal bracing and usual installations of glue blocks at the junction of walls. The enclosure should be constructed of three-quarter inch plywood or particle board. Although particle board represents more weight in the finished enclosure, its density, lack of resonance, and low cost make it the choice of most manufacturers. While the exact dimensions are not critical, the builder should avoid having any dimension more than three times another dimension to avoid standing waves. The port tunnel fits into the receptacle so that one end is flush with the front of the baffle panel. The tunnel length includes the total distance from the front of the baffle panel to the opposite end inside the cabinet. At least 50 per cent of the interior surface should be lined with two inch thick insulation such as fiberglass. The exact amount needed will be determined by the sound of the system in the listening area (4, 8, 9). It may be desirable on the smaller ducted-port enclosures, to staple a sheet of insulation over the back of the loudspeaker much as a blanket would cover the speaker. Care must be taken to avoid the insulation touching the diaphragm causing restriction of its free movements.

Mounting the Loudspeaker

Larger low frequency drivers normally found in bass reflex enclosures must be rigidly mounted to the baffle board. Best results are obtained when speaker frames are attached with tee nuts. Eight one-quarter inch by twenty threads

T-nuts will usually support the larger woofers; but for very massive woofers to be installed in musical instrument enclosures, the largest bolt diameter that will fit through the holes in the speaker frame may be desirable. Every mounting hole in the speaker frame should have a mounting bolt on a T-nut, fastened securely to the baffle board. Excessive torque may warp the loudspeaker frame and cause serious damage to the loudspeaker. It is necessary to make sure the mounting bolts are tight, but do not crush the gasket. Manufacturers differ as to whether front or rear mounting of the speaker is more desirable. Refer to the manufacturer's technical sheet accompanying the loudspeaker for installation recommendation. A removable front baffle board is almost always more desirable since it may be removed for alteration, testing, and bracing of the system.

Summary

The bass reflex enclosure, by nature of its adaptability, is the most practical choice for the custom builder. Bass reflex enclosures may house one speaker or a multiple speaker system. It can be constructed sturdy enough to house the most powerful musical instrument monitor system without losing portability. Sizes of cabinet volumes may be easily determined by the builder as he attempts to match a particular speaker. The damping and tuning processes are functions easily achieved with this type enclosure.

Although most bass reflex enclosure systems exhibit some lower mid-bass bumps or peaks, many listeners become used to the sound and actually prefer its slight coloration. Bass reflex enclosure systems are more efficient than acoustic suspension systems but their relative efficiency rarely approaches ten per cent. All direct radiator speaker systems are inefficient. The bass reflex enclosure port helps load a speaker at lower frequencies; but to achieve this loading, many parameters must be juggled and critically adjusted. There is a more complex,but much more efficient,method of transforming electrical energy into acoustic energy, the horn-type enclosure.

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CHAPTER V

HORN TYPE ENCLOSURES

The horn, as an acoustic baffle, has been used by man since antiquity (10, p. 159). It became known to the ancients that more efficient volume could be gained from the voice simply by cupping both hands around the mouth. The first artifacts used as horns were probably the horns of animals. Later utilization of metal for construction of horns made possible the variation of sizes, shapes, and tapers. Horns were primarily used as signaling devices or hunting calls. Later development of designs led to their use as musical instruments. Most all wind actuated musical instruments use some form of horn-type expansion in their design.

Early experiments by Edison, at sound reproduction with the use of wax cylinders, included the application of a short conical horn to acoustically increase the playback volume. Most homes by the 1920's had a "morning glory" horn connected to their radios or phonographs. Webster patented the first exponential horn in 1919 (6, p. 116). After years of research and development, Klipsch marketed the first folded corner horn in 1940 (8, p. 4). The importance of this achievement in the development of horns was twofold: First, the extremely long axis of the straight horn was folded around itself making possible a more usable size enclosure, and second, the size was further reduced by utilizing the corners of a listening area as a natural extension of the horn's mouth. The mouth of the horn did not need to be terminated at the edge of the enclosure but could be shortened by the use of ninety degree flare of the adjacent walls.

Acoustic Theory of Operation

All direct radiator speaker systems are inefficient. They use different methods to achieve efficient coupling of the diaphragm to the outside air. Whether a multi-driver infinite baffle or bass reflex is used, the diaphragm is still relatively small compared to the outside air. The impedance match is a poor one and the efficiency is low. A more efficient impedance between diaphragm and air can be realized by attaching the diaphragm to a constantly expanding flared tube. Because of the efficient bite on the air, resonance of the cone is lowered and the cone can work much more slowly (3, p. 168). By using the flared transmission channel, the effective radiating area of a source of sound can be increased to that of the mouth or large open end (13, p. 84). The mouth of the horn is coupled to the driver or speaker. The horn's flare rate of expansion is fixed by a mathematical formula, that if properly designed, will yield high efficiency, uniform response, and very little distortion (5).

The horn is an acoustic transformer, not an amplifier. The reason sound emanating from the mouth of a horn is louder than the sound introduced at the throat of the horn is because the driver realizes an efficient impedance match with the air as the sound waves travel along the length of the air column. When the driver is coupled to the throat of a horn, all of the frontal diaphragm is six times as large as the narrow mouth opening, thus the compression ratio will be six to one. In practice, most driver to throat ratios will be around two to one; that is, the driver diaphragm area will be twice the area of the throat.

Forcing sound from a piston through an opening half its size creates a high pressure and a correspondingly high volume velocity. The natural resistance of the constricted throat area results in a high pressure across a high impedance at the small end of the horn. As the sound waves move down the continually expanding transmission channel, pressure decreases until the wave leaves the mouth to radiate into space. This lower pressure at the mouth is accompanied by a low impedance. Transformation of high throat impedance into low mouth impedance makes the sound wave more compatible with the impedance of the outside air. The specific acoustic impedance of air is about forty-two acoustic ohms (4, p. 199). Since the mouth area of a horn is many times the area of a loudspeaker diaphragm, it has a decided advantage in the movement of air at lower frequencies over that of direct radiator speaker type baffles. Figure 15 illustrates the transformer characteristics imparted to the air column by the flaring horn.

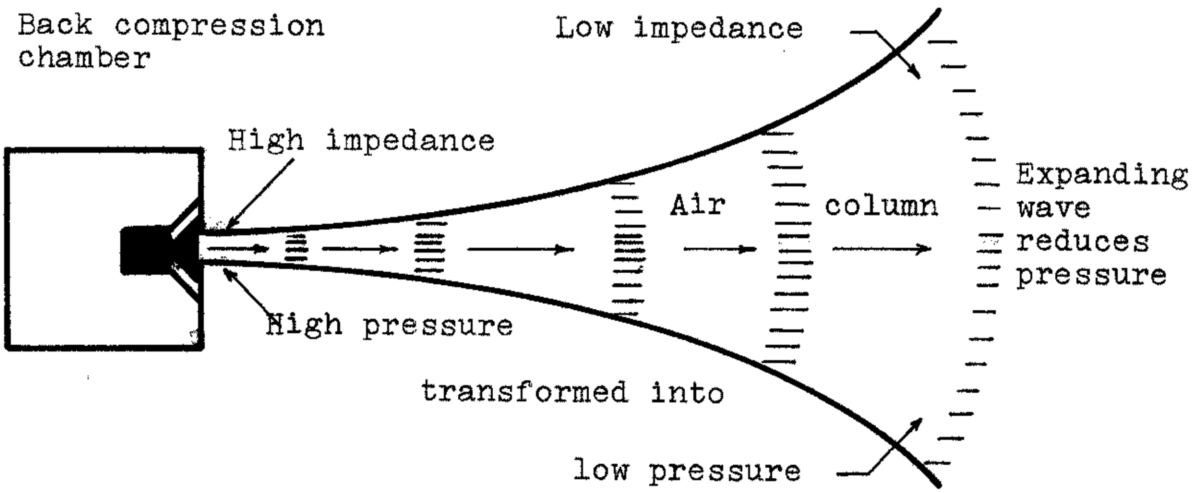

Fig. 15--Transformer characteristics of a horn

Horn Shapes and Cutoff Frequency

The horn is essentially a high pass filter in that it readily passes a band of frequencies above its cutoff frequency. Below its theoretical cutoff frequency the horn does not operate. For practical purposes of sound reproduction, a cutoff frequency somewhat higher than the theoretical one must be chosen because at a point about twenty-five per cent above the theoretical cutoff, horn loading begins to fall off sharply until it reaches zero.

There are many horn flare rates, all of which affect the band of frequencies they will pass. Four most commonly used horn shapes or flare rates are shown in Figure 16.

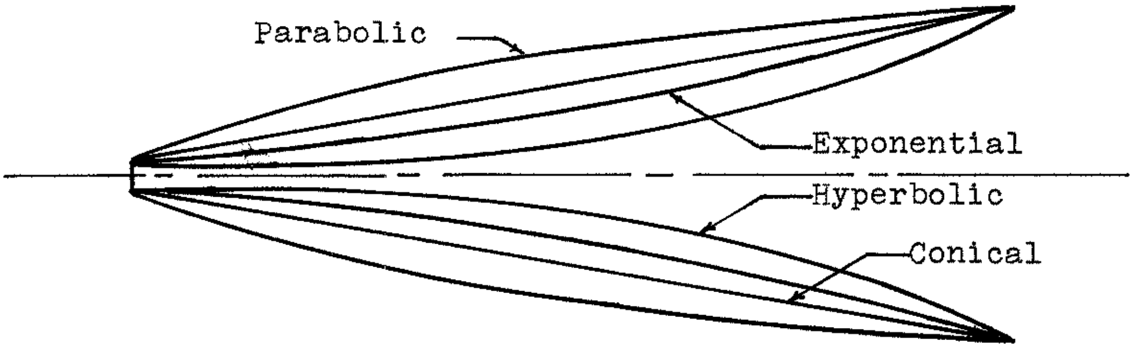

Fig. 16--Four horn shapes

Horns With an Identical Cutoff Frequency

Parabolic horns--expand the quickest to reach a desirable throat impedance. They have the advantage of reaching a higher efficiency but as their expansion rate slows toward the mouth, they develop internal non-linear distortion characteristics.

Conical horns--expand quickly at a constant rate. They have fairly high efficiency but develop serious overtones in the lower frequencies. These overtones, however, are useful and desirable in musical instruments such as trumpets, french horns, and organ pipes (11, p. 266-268).

Hyperbolic horns--expand slowest overall. They immediately rise to optimum radiation resistance then rise at a slow rate to insure good low frequency response. Hyperbolic horns exhibit some non-linear distortion at very high volume levels but otherwise are frequently used as woofer and tweeter horns in hi-fidelity applications (1, p. 87-88).

Exponential horns--have an expansion rate rapid enough to keep pressure and distortion within limits. Its frequency response does not roll off until much later than the other horn shapes. It does not have quite the low frequency response of the hyperbolic horn, but it exhibits less distrotion at high volume levels. The exponential horn is an engineering compromise that is the most frequently utilized horn shape (1. p. 87-88).

The length of the horn's axis is also an important factor in determining which frequencies will develop and pass through the horn and which frequencies will not. For a horn of a given length, there are wave lengths of sound such that, before a wave pulse can start to build up in the throuat, the previous wave has already exited the mouth. At these frequencies, the transfer of sound waves cannot be built up as they traverse the air column. The transformer effect cannot take place and for all practical purposes, the horn does not exist at these frequencies. If the frequency is raised to a point where several wave lengths have an opportunity to build up within the horn, the high throat pressure will push each successive wave toward the mouth of the horn. The frequency where the transitions between the pass or no-pass condition of a wave is decided is the theoretical cutoff frequency (12, p. 145-171).

Another factor determining the frequency a particular horn will pass is the area of the throat. For a circular horn, the diameter of the mouth should be one-third wave length of the actual sound to be transmitted (4, p. 238). It is for this reason bass horns flare slowly terminating with large mouths and tweeter horns flare quickly terminating with small mouths.

Design Calculations

Tweeter horns are seldom custom constructed because they are usually designed and fitted to the high frequency driver at the factory. Also, since tweeter horns have to be designed with consideration to their high frequency dispersion characteristics, it would be beyond the scope of this paper to investigate the mathematical calculations and theoretical data necessarily involved. The building of a bass horn is a very difficult task, but the fact that we are dealing with longer wave lengths and larger, more calculable dimensions, makes the project more feasible.

To design a woofer horn, the lowest actual wave length should be determined by the formula (7, p. 19):

$$\lambda \text{ feet} = \frac{1128 \text{ ft./sec.}}{30 \text{ cps}} \quad \begin{matrix}\text{(Approximate speed of sound)}\\ \text{(Lowest frequency desired)}\end{matrix}$$

$$\text{then: } \frac{1128}{30} = 37.60 \text{ feet for a 30 cycle tone}$$

Divide this number by three to determine the diameter of the mouth.

$$\frac{37.60}{3} = \begin{matrix}\text{12.53 feet = diameter of mouth}\\ \text{necessary to reproduce a 30}\\ \text{cycle tone}\end{matrix}$$

The variations in dimensions of different shaped mouths (square, rectangle) are covered in Appendix J.

The next consideration should be the throat size and area since the size of the slot will determine crossover frequency. Crossover frequency should be chosen according to the response of the high frequency drivers to be used with the bass woofer. It should also be determined by output characteristics of the woofer in the 500 cps region as well as the length of horn that can be tolerated. For a three way system, a crossover somewhere in the 500 cps region is standard (9, p. 204-209). To compute the correct throat area, it is necessary to know speaker design data not normally available to the custom builder, therefore, the general rule for throat area is to make it half the size of the diaphragm area (4, p. 245).

The most commonly used horn for bass reproduction is the exponential horn. One of its characteristics is that the increase of its cross sectional area is proportional to its length. In other words, if the cross sectional area ten inches from the throat is forty square inches, the cross-sectional area twenty inches from the throat will be eighty square inches, and thirty inches from the throat will have a cross sectional area of 160 square inches. This means that the cross sectional area doubles every ten inches of horn axis length. This is known as the doubling distance (dd). The basic equation defining an exponential horn shape is (2, p. 195):

$$\frac{A_x}{A_t} = e^{mx}$$

A_x = the cross sectional area at distance x from the throat in square inches,
A_t = the cross sectional area of the throat, in square inches,
e = the natural logarithm base, 2.7183,
m = the flare constant of the horn, in inverse inches,
x = the distance from the throat, in inches.

The importance of the equation is primarily to find the flare constant (m). The flare constant determines how long an axis the horn will need to pass a chosen low frequency. The cutoff frequency depends upon the flare constant as (2, p. 196).

$$f_c = m\frac{V}{4\pi} \qquad \text{or} \qquad m = \frac{4\pi f_c}{V}$$

f_c = cutoff frequency, in Hz,
m = the flare constant in inverse inches,
v = 13,500 inches per second, the velocity of sound in the air

A convenient method of stating flares is to plot the distance along the axis of the horn over which the cross sectional area doubles. Doubling the area is the same as multiplying the diameter by 1.414, which is the square root of two. It is best to use linear measurement in inches when laying out horn patterns of a practical size. Appendix K represents the plotted exponential curves for the layout of a high frequency horn to be used with an Altec 808-8A, 800 cps high frequency driver in a two-way system. It should be apparent that a low frequency horn must be longer with a slower flare rate than a high frequency horn with a short axis and a rapid flare rate. A rapid flare rate for a high frequency horn helps in the dispersion of the shorter, high frequencies. Because of the extreme wave lengths that a low frequency horn must radiate, narrow band dispersion is never a problem in designing bass horns.

Appendix J (4, p. 236) is a list of tables which contain design data for use in constructing bass horns with various cutoff frequencies. It covers expansion rates and mouth dimensions for several different shapes of horns. Note that some of the larger dimensions are given in feet rather than inches. This appendix contains some of the design formulae discussed previously in this chapter, but in a more tabulated form.

Column A lists the actual cutoff frequency desired by the builder. Note that this actual cutoff frequency is 25 per cent higher than the theoretical cutoff frequency in Column B. The reason for this difference is that at theoretical cutoff frequency, the output of the horn is zero. Efficient horn loading does not begin to occur until the frequency is at a point about 25 per cent higher than the theoretical cutoff frequency.

Column B contains a corresponding list of theoretical cutoff frequencies. These frequencies are the ones which are to be used in design calculations for a horn.

Column C indicates the percentage increase in cross sectional area of the exponential horn for the theoretical cutoff frequency listed in column B. This increase, measured axially along the horn, is given in one-inch as well as one-foot increments. Normally, one would use the one-foot increments to lay out the flare of the horn; if, however, the horn is to be folded design, accuracy around the bends will necessitate the use of one-inch increments. It is best to use the expressions for area increase-per-inch when working in small parts of the horn and area increase-per-foot when working in the large parts of the horn. Once the horn cutoff frequency has been determined, the horn may be laid out on paper. The amount of cross sectional area can be plotted in relation to the increase in distance along the axis.

Column D indicates various wave lengths for the frequencies in column A.

Column E gives the minimum diameters and areas for a circular mouth. Diameter of the circular horn mouth is figured as one-third the wave length listed in column D.

Column F determines the first practical termination of the horn as the tabulated areas of cross section are laid out per increase in length of horn. The increases in area per length are simply laid out along an axis until the desired mouth area is reached. That point becomes the terminal length of the horn.

Columns G and H serve the same function as columns E and F. They take into consideration the adjustments that must be made when building a square shaped horn. The square mouthed horn uses the same wave lengths for the mouth perimeter from column D, then divides them by four. To arrive at the same termination point as the circular horn, the square horn will necessarily be somewhat shorter in length. It will therefore have slightly less efficiency than the circular horn.

Column I gives the side dimensions for a square-mouthed horn. The perimeter length has been adjusted to longer than one wave length. This corrects for loss of efficiency from the circular to square shaped horn configuration.

Column J indicates the minimum short side for the rectangular horn based on the same factors determining side length for square horns. In addition, minimum length for the longest side of the rectangle is given to achieve mouth area equal to a corresponding size circular horn.

Construction Considerations

The large advantage gained in efficiency by the use of horn loading a speaker enables the driver to work about one-fourth as hard as it would in an acoustic suspension system. The front of the speaker diaphragm is in contact with a high mass load of air in the horn. At the same time, the absence of a load on the rear of the diaphragm represents a very unequal load to the front and rear of the speaker. This design problem can be solved by the construction of an air chamber around the rear of the speaker. This back chamber performs two functions. It helps keep a balanced load on the rear of the speaker cone somewhat equal to the load presented to the front of the speaker. This preserves linearity of diaphragm motion which in turn reduces distortion. For the custom builder, the most commonly accepted rule for determining back chamber volume is that its size be equal to (4, p. 249):

Back chamber volume $V=3 \times t_a \times dd$

V = volume of air chamber

t_a = throat area, in square inches

dd = horn length for area to double (doubling distance)

Phasing of Multi-speaker Horn Systems

Construction of a large bass horn will mean the builder will be dealing with a very large enclosure and extremely long wave lengths. A large folded corner horn with a cutoff of thirty cycles could have a linear distance from throat to mouth of sixteen feet. The corresponding distance on a 500 cycle midrange horn may be two feet and the same for a 3500 cycle tweeter horn, three inches. It is obvious that if a tone were struck simultaneously by all three drivers in the three-way system,there would be a noticeable time lag between the outputs of the three horns. To try and reduce this time lag,the midrange driver should be located behind the front plane of the bass horn's mouth. The tweeter horn driver should be located as far back from that plane as physical space will permit. This re-location of driver units will help sounds eminating simultaneously from a three-way horn system to reach the listener's ears at more nearly the same time.

Bracing

The horn is a high compression baffle. A large monitor horn system develops tremendous acoustic pressures within the horn. The very nature of a horn's characteristics makes it suited for high volume application. Any flexure of horn walls will seriously deteriorate the acoustic wave transmission. Rigidity and accuracy are vital factors in the quality of horn performance. The compression back chamber should be sturdy enough to tolerate very high back pressures. The speaker mounting board must be gasketed before being installed in the horn.

Damping

Horns are seldom designed with parallel walls that could produce internal standing wave destruction. Sound absorbant material attached to the horn's wall would deteriorate proper wave production. It may be necessary sometimes to install sound absorbant material to the interior portion of the back chamber, especially if the volume is small and the rear of the driver is in close proximity to the walls.

Advantages and Disadvantages of Horn Systems

Efficient use of the driver output can make a well-built horn system perform truly impressive sound reproduction. A properly coupled horn and driver will deliver relatively distortionless low frequency sound output from a whisper to auditorium monitor listening levels. Many different horn-type systems are used all over the world where high volume levels and highest quality reproduction applications dictate.

One of the disadvantages of custom building a horn system is the need for extreme accuracy in the design calculations and construction techniques. Another disadvantage is that the horn cannot be tuned or adjusted once it is built. Horns do not have the flexibility of infinite baffles or bass reflex enclosures.

If the builder is acquainted with a knowledge of physics and mathematics in addition to having considerable experience in woodworking, he will be prepared to begin a very ambitious project that if completed correctly, will give him a return in sound reproduction of the very highest quality.

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CHAPTER VI

ENCLOSURE CONSTRUCTION DETAILS

The choice of an enclosure must be made on the basis of weighing several criteria. Performance, appearance, style, size of listening area, and cost, all must be determined before the type of enclosure may be decided upon. A feature that should be built into any system is flexibility of expansion or change at a later date. It is much easier to build an enclosure capable of housing the addition of more or higher quality components than it is to reconstruct an inadequate enclosure to accept an upgraded system. Since the cost per watt is considerably lower than the earlier days of hi-fidelity, the efficiency of a speaker system should have little bearing upon choice or quality. Efficiency, however, is usually a clue to the ultimate size enclosure needed to house the speaker system. Although not always the case, low efficiency systems suggest the bookshelf size enclosure while higher efficiency systems may be any size ranging from three cubic feet to beyond fifteen cubic feet.

Construction Material and Techniques

Easily the most important consideration in the construction of any speaker enclosure is its rigidity. Smaller enclosures will develop less problems of wall flexure because of the smaller panels used in construction. A small bookshelf enclosure may be satisfactorily built out of three-eighths inch to five-eighths inch thick material. Proper damping and bracing would avoid the occurrance of any spurious buzzing or wall flexure. Infinite or bass reflex enclosures having any panels larger than three square feet will need to be divided by a reinforcing strip to reduce resonance or drumming at low frequencies (4, p. 4). Larger enclosures are usually constructed with three-quarter inch thick plywood or particle board panels. A technique sometimes employed to utilize the acoustic deadness of particle board and yet display a furniture finish on the outside of the enclosure, is to cover the outside of the particle board with a one-quarter inch thick hardwood veneer. The veneer may be finished and the wall thickness then becomes one inch, which improves rigidity. Early attempts by audiophiles to gain absolute rigidity produced designs such as, speaker systems being mounted in bricked-over fireplaces, and cabinets of double wall thickness, with the space between filled with sand. Better building materials and strict attention to construction details should eliminate the need for such extremes.

Bracing and Joinery

Whether the enclosure is a complicated horn or a simple direct radiating bookshelf system, it must be built true and tight. The type of cabinet joint used to mate adjoining walls is usually left to the discretion of the builder. Certain materials such as particle board are better suited to the simpler cabinetmaking joints because of brittleness at its edge and corners. It is therefore suggested that rabbet butt, and butt-miter joints be considered when construction is to be out of particleboard or flakeboard. Figure 17 shows some typical cabinet joinery frequently used by commercial manufacturers of speaker systems enclosures.

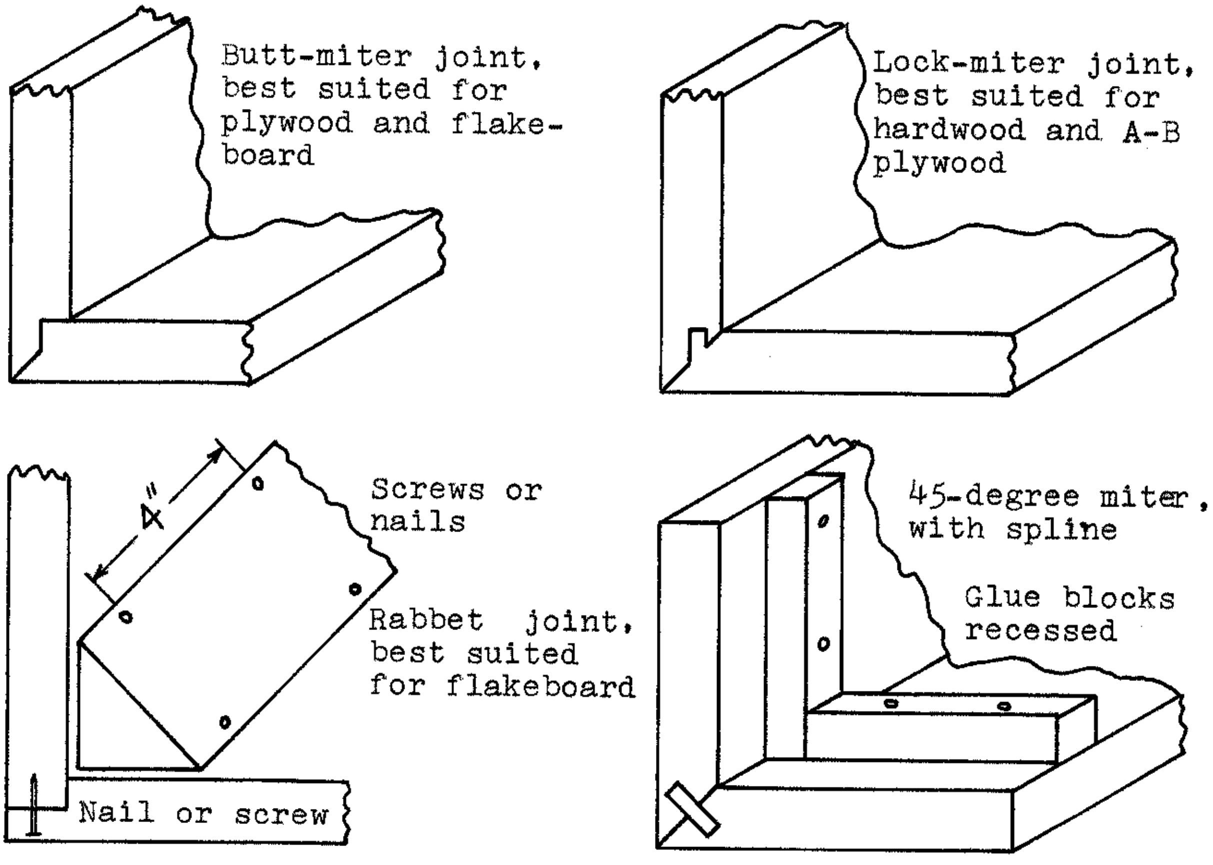


Fig. 17--Typical enclosure joinery

Nearly all manufacturers agree to the importance of having an air tight enclosure at all points except deliberate openings such as ports, exponential horns, etc. Avoid creating any restrictions or cavity openings not called for in the plans. All adjoining panels, except removable ones, should be reinforced with glue blocks or scabs running the entire length of the joint. These blocks should be painted with glue and screwed into the joint at three-to five-inch intervals. Accumulation of small air leaks may develop objectionable wheezes, hisses,or whistling,especially at lower frequencies. It is important to remember to run adequate bracing between front and rear panels as shown in Appendix F. When holes are cut into the speaker baffle mounting board, the panel suffers a certain amount of weakness between the cutouts. A two-by four-inch interior brace,running horizontally from rear panel to the front speaker mouting board,should restore the rigidity lost when the cutouts were made.

Damping Techniques

Interior volume, shape, and acoustical treatment play an important part in the speaker system/enclosure reproduction. Nearly every manufacturer suggests that no cabinet dimensions be more than three times another (11, p. 4; 14, p. 3-6). The reason for this rule is that parallel opposing walls within an enclosure can create undesirable resonances or pipe organ effects called standing waves (1, p. 130). As the waves leave the rear of the diaphragm, they will reflect off the rear wall and bounce back into the speaker cone. Standing waves, especially prevalent in elongated enclosure shapes, cause serious irregularities in frequency response. The possibility of these standing waves is the main reason most all manufacturers locate their low frequency drivers several inches off-center of a speaker mounting baffle board (3, p. 227). Enclosure designs that employ irregular shapes are usually attempts by manufacturers to help eliminate standing waves. Triangular shaped enclosures which fit into corners are attempts to solve the problem by presenting non-parallel opposing walls to the rear of the speaker cone (7, p. 46-48). One of the best and most effective methods in reducing standing waves within an enclosure is the liberal treatment of the interior with some sound absorbing material.

A high compliance acoustic suspension system may need its enclosure nearly filled with acoustic damping material. When fully stuffed with acoustic lining, the acoustic suspension enclosure behaves as though it were 1.4 times larger. The result is a slowing down of the sound within the enclosure and a lowering of the speaker's resonant frequency (15, p. 54). Most bass reflex enclosure systems require fifty per cent of the interior walls be lined with a soft, fluffy, absorbant material (4, p. 7). The lining is usually arranged so that a padded wall faces an unpadded wall. The type of driver chosen,as well as the reverberant nature of the listening room, may require the builder to line nearly all interior walls of the bass reflex enclosure. Experimentation with damping insulation will probably be the best way of custom tuning the system to the particular listening area. In any case, the loudspeaker mounted walls will almost never be lined with damping material.

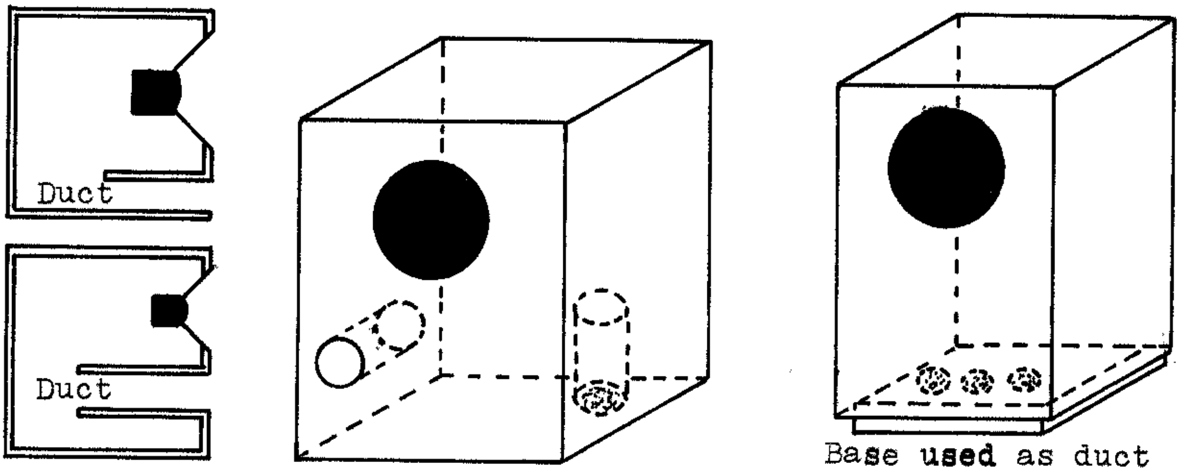
Two inch-thick fiberglass is most commonly used for damping because of its availability at most sound centers and hardware stores. If only one-inch thick material is available, it may be doubled or used as one-inch damping. Altec recommends fiberglass with a weight of about six pounds per cubic foot (14, p. 5). Damping material may be glued to the interior walls with contact cement, or it may be nailed, or stapled to the surfaces. If the fiberglass has some kind of backing, staples will hold it securely to the walls. One of the best methods of securing the fiberglass to the interior walls is to cut small cardboard washers about one-inch square. Staples or nails should be placed through the cardboard washers, then, through the acoustic lining, to secure permanently the acoustic treatment. While fiberglass is most commonly used for damping, James B. Lansing Sound states that:

> . . . any other soft, fluffy, absorptive material (such as Kimsul, Tufflex or felt rug padding) will do equally well. . . We do <u>not</u> recommend that you use Celotex, foam rubber, styrofoam, rock wool, acoustic tile, cork, cotton, rubberized rug padding, or kapok (4, p. 7).

Whichever materials and methods of installation are chosen by the builder, the use of acoustical damping will improve the transient response and overall smoothness of the system.

Duct and Port Calculations

Ducted ports and vents used in phase inverter baffles are calculated with a direct relationship to loudspeaker resonance and projected enclosure volume. Internal volume may be expressed in cubic inches or cubic feet. Enclosure volume may be computed by multiplying width times length times depth of inside dimensions. The conversion of cubic inches into cubic feet may be figured by dividing the total cubic inches by 1728 (one cubic foot). Many nomograms have volumes expressed in cubic feet so it is important to be able to compute in either system. Once the enclosure volume is determined, the correct port or duct may be chosen from one of the tables in Appendix E. The shape of the port or duct to the front of the enclosure is not as important as the cross sectional area, or total open area, in square inches. For example, port openings calling for sixteen square inches could be cut out three inches by six inches, four inches by four inches, or any combination of figures that would conveniently fit the speaker mounting baffle board. If a circular port is desired, the formula, Area $=\pi r^2$, may be used to determine the cross sectional area of the opening. The required length of a circular duct may be chosen from Appendices G, H, and I (12, pp. 55-56). Measurement of the duct length should include the thickness of the baffle board to which it is attached. A rectangular or square shaped duct is most easily constructed from one-quarter inch thick plywood. This thickness material will suffice if its outside corners are braced and it is secured to the baffle board with glue blocks. A 10 per cent variation in port opening or duct length will probably have little effect upon speaker system performance. An ordinary cardboard mailing tube may be used for a circular duct. These mailing tubes are normally available in diameters of two, three, and four and three-quarter inches. The proper tube to choose should be the largest inside diameter possible which will still give a tube length of at least one and one-half inches in length (1, p. 81). The port or duct may be positioned anywhere on the front speaker baffle board as long as it is not closer than three inches to the woofer. Figure 18 shows some variations in the location of ducts for a bass reflex enclosure.



Base **used** as duct

Fig. 18--Location of ducts

Convenience of installation and availability of woodworking machinery should determine duct location and installation.

Mounting Hardware and Wiring Terminals

As stated in previous chapters dealing with specific enclosure types, loudspeakers should be mounted on the baffle board with T-nuts. Figure 19 shows typical front and rear mounting of loudspeaker to baffle board.

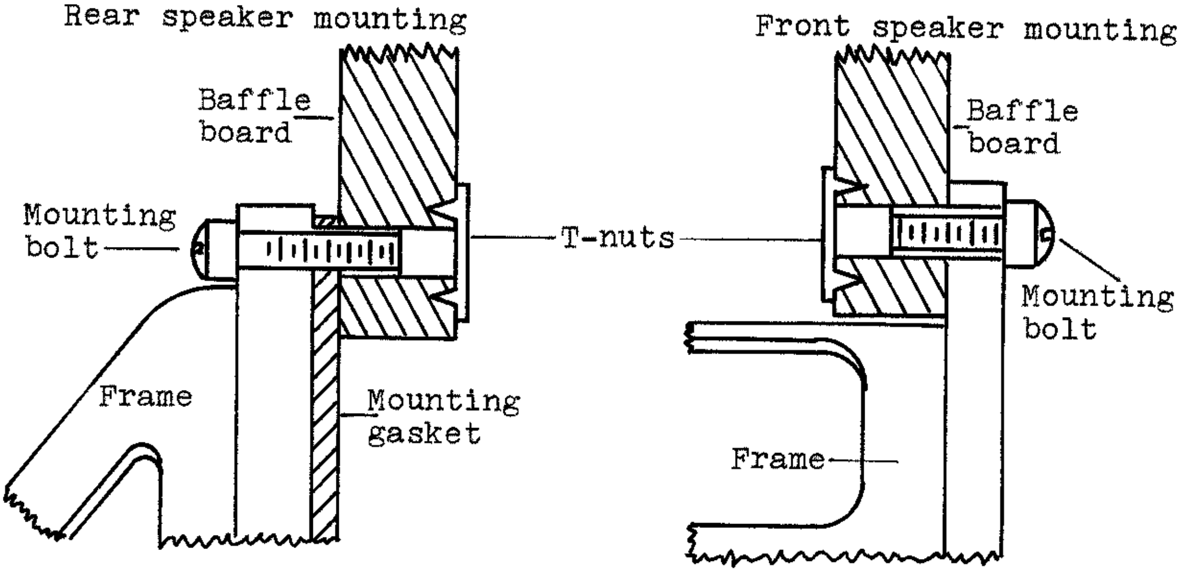


Fig. 19--Correct methods of speaker mounting

High frequency units should likewise be baffle-mounted with T-nuts near the top of the enclosure as close to ear level as possible (6). Installation of diffraction horn-type tweeters should be made with long-axis in vertical position for maximum horizontal dispersion (5, p. 13). Most speaker manufacturers have their own installation bulletin accompanying the speaker in the shipping carton. If, however, the builder is dealing with raw speakers, the following standard loudspeaker cutout and mounting hole diameters will be helpful. Figure 20 lists the most common woofer mounting dimensions (12, p. 69; 14).

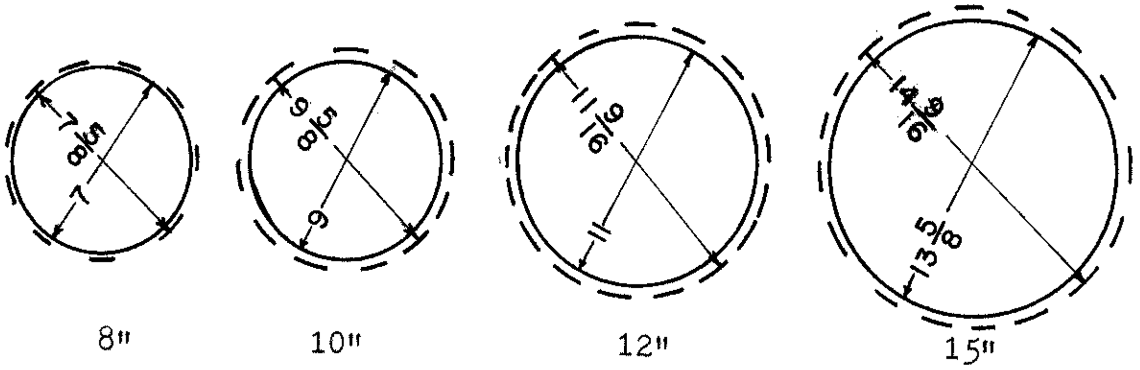


Fig. 20--Standard speaker mounting diameters

Excessive overtightening of any transducer mounting bolts could cause enough warpage to allow the voice coil to rub against the magnet pole pieces, causing serious speaker damage.

Wiring of the speaker system should be secured by any one of the three methods:

1. Screw-down terminal provided on some loudspeakers
2. Slip-on, crimped, spade lugs
3. Wire passed through hole in terminal lug, crimped down tight with pliers, and securely soldered

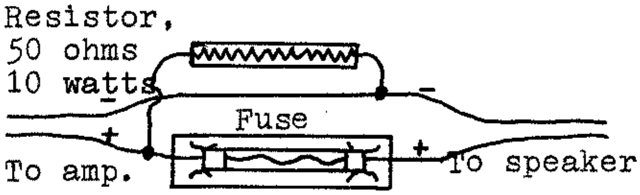
Alligator clips or wire wrapped around terminals are not satisfactory methods of making speaker connections. Air leaks from the holes where speaker wires exit the rear of the enclosure can be eliminated by installation of a standard terminal strip or a one-quarter inch diameter phone jack.

The cone assembly should not be moved by hand, as it may cause serious damage to the suspension system. Care must be taken to see that no foreign particles enter the magnetic assembly of the loudspeaker. This is especially important when mounting high frequency diffraction horns because their magnetic gaps are open to the air. The magnetic field can easily attract ferrous particles down the throat of the horn into the magnetic gap.

Electrical Wiring Considerations

Power Handling Capacity

Power handling capacity listed for a particular speaker usually refers to continuous program material. The actual maximum power a speaker is capable of withstanding may actually be twice the rated power capacity. It is important to determine the precise meaning of the manufacturer's power rating of the particular speaker to be used. Large magnetic assemblies found on heavy-duty woofers are capable of dissipating much more heat than the light, magnet assemblies of a tweeter. Just as the tweeter has to be protected from low frequencies entering its coils, heavy woofers must also be protected from accidental or excessive peak surges. Fusing a speaker system offers some protection against overload. One way of protecting the speaker system is to use the Littelfuse method. Low current fuses are placed in series with each driver unit. Shunted across the fuse is a resistor of fixed value equal to the rated resistance and power of the speaker (16, p. 10). An easier method of protecting a speaker system is shown in Figure 21 (10, p. 58).



Speaker power rating		Fuse rating in amperes		
		4-ohm speaker	8-ohm speaker	16-ohm speaker
7-10 watts	safest	½	¼	1/8
	good	1	½	¼
	maximum	2	1	½
10-15 watts	safest	3/4	3/8	¼
	good	1½	3/4	3/8
	maximum	3	1½	3/4
15-25 watts	safest	1	½	¼
	good	2	1	½
	maximum	4	2	1
25-35 watts	safest	1½	3/4	3/8
	good	3	1½	3/4
	maximum	6	3	1½
35-50 watts	safest	2	1	½
	good	4	2	1
	maximum	8	4	2
50-75 watts	safest	2½	1½	3/4
	good	5	3	1½
	maximum	10	6	3

Fig. 21--Fuse protection values for speaker systems

Standard 3AG fuses should be used, not slow-blow types. The first choice of fuse values should be the safest recommended value. If the fuse blows on loud passages, the next value should be substituted. The lowest rating that will not blow offers the best protection to the system, while too high a value offers no protection at all.

Most accidental damage to speaker systems can be avoided by observing these rules:

1. Do not use household a.c. plugs for speaker connections.
2. Do not turn amplifier off or on with the bass control turned all the way up.
3. Do not connect or disconnect amplifier input cables with volume at high levels.
4. Do not drop tonearm and cartridge on record while amplifier volume is set high.
5. Make sure there are no loose input or output connections of any kind.
6. Turn down volume during high speed re-wind or fast foreward of tape recorder.

Wire Sizes and Cable Lengths

When transmission lines are connected directly from amplifier to speakers they are called low impedance lines. Low impedance lines have the advantage of little loss of high frequency gain up to about 200 feet (16, p. 16). Figure 22 indicates recommended wire size for different length cable and different impedance speakers.

Wire Size	Load Impedance		
	4 ohms	8 ohms	16 ohms
14	125 ft.	250 ft.	450 ft.
16	75 ft.	150 ft.	300 ft.
18	50 ft.	100 ft.	200 ft.
20	25 ft.	50 ft.	100 ft.

Fig. 22--Maximum length of line for 15 per cent power loss-low impedance

Speaker Wiring Connections

It is important that polarity be observed when connecting speakers. Wires may be terminated with spade lug connectors or simply crooked on end and tinned with solder. Either way, the connections from amplifier to speaker system must be secure, for the sudden open circuit transmission line to a speaker could cause severe damage to the output stages of an amplifier. For single speaker connections, the rated speaker impedance should equal the amplifier output impedance. For series connections, the total impedance will be the sum of the impedances of the number of speakers used. For parallel connections, the total impedance will be that of a single speaker divided by the number of speakers used (13). It is best to use speakers of the same rated impedance in a system. Mixing impedances may lead to electrical problems and performance deficiencies. Figure 23 shows some speaker wiring methods used to achieve proper impedance matching.

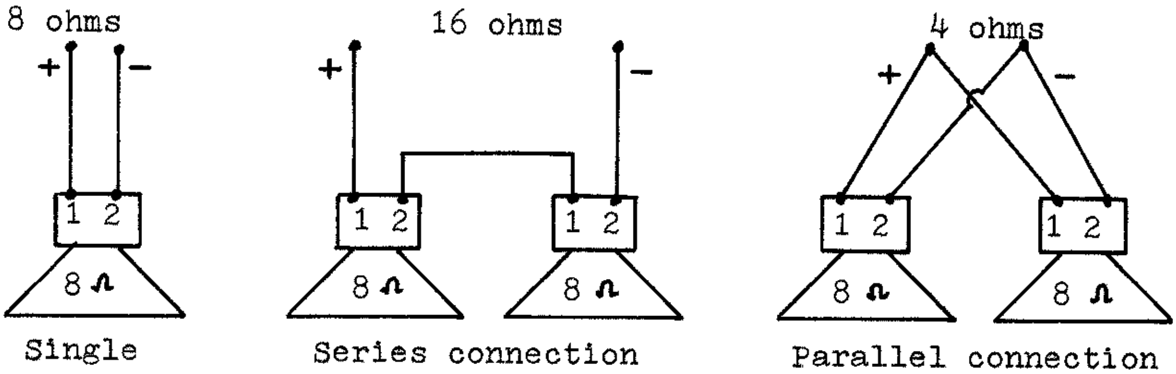


Fig. 23--Illustrated speaker wiring connections

Grille Assembly

The front of all speaker systems should be covered with a grille assembly to help protect the speakers from accidental damage. Standard speaker grille cloth is best, however any loosely woven fabric may be used as long as it has at least 50 per cent open area. Acoustically transparent grille cloth will allow the high frequencies through, where a more densely woven fabric tends to muffle those frequencies. The grille cloth may be stretched on a frame so as to be easily set in place or removed. Magnetic catches, friction clips, or Velcro will hold the grille assembly securely to the cabinet. Any decorative grille cloth must be stretched tightly over the frame assembly or it will vibrate against the front panel during the playing of low frequency program material.

Testing the Speaker System

Once the drivers are properly mounted in the enclosure, final testing of the whole system may begin. Tests for resonant peaks ideally should be carried out with the equipment discussed in chapter four concerning bass reflex enclosures. Once the port and damping adjustments appear to be optimum, listening tests may be undertaken to check the ability of the system to reproduce music. Appendix L lists some recordings frequently used by audiophiles in testing speaker systems (9, p 60-63). A recording such as the Shure Stereo Test Record will provide a variety of sounds and tones with which the builder may check for spurious buzzes or rattles. Low frequencies played at high volumes are the best method of locating any air leaks or weakly braced panels. With the volume fairly high, the outside panels of the enclosure should be felt for excess vibration (1, p. 134-135; 8, p. 204-209). These points will need additional bracing. An excess of bass may mean additional acoustical damping is necessary. Boomy or sluggish bass response may mean the bass reflex system, as it relates to the particular listening room, requires a smaller port area. Excessive puffing of low frequencies may mean an adjustment in duct length is necessary.

High frequency dispersion may be determined by the introduction of "white noise" (2, p. 45) through the speaker system. "White noise" is most easily obtained in the form of interstation hiss on the FM tuner. This test of high frequency dispersion will reveal if the physical location of the tweeter is high enough from the floor. The tweeter should be placed as close to ear level as possible to achieve high frequency efficiency. Attenuation of the highs may be achieved by adding a potentiometer to the tweeter circuit. It is important that phasing between woofer and tweeter,as well as phasing between two stereo speaker systems, be uniform so that during a given signal from the amplifier, all diaphragms in all the speaker systems be moving the same direction. Failure to check phasing will result in some bass loss.

The Room As Part of the Acoustic Circuit

Placement of the speaker system in the room will have much to do with the overall sound reproduction. Walls and floors reflect sound much as a mirror reflects light. Placement of a speaker system on the floor will improve bass response somewhat, but the placement of the system at the intersection of a wall and floor will improve the bass response even more. The most bass re-enforcement may be obtained with the system situated at the juncture of three planes such as the corner of a room. Corner placement also helps in the reduction of standing waves within the listening room.

The amount of damping in the listening area will affect natural reverberation time. Drapes, carpet, overstuffed chairs, and people,will all contribute to the "deadening" of a room. In addition, their sound absorption characteristics will most affect high frequencies,making it necessary to adjust tweeter output.

Sources of Acoustic Data

This paper serves only as a general guide for the prospective enclosure builder. Frequent changes in design and manufacturing methods make it impossible for these data to apply to every speaker system. In addition, specific requirements or techniques suggested by manufacturers of a particular loudspeaker will supersede the data accumulated in this paper. It is therefore wise to refer any questions concerning specific problems of a loudspeaker or system to its manufacturer. The technical service departments of most manufacturers will readily respond to any questions or difficulties encountered by the builder. Appendix M is a list of some of the larger manufacturer's technical service departments available if needed. A close adherance to the data collated in this paper, as well as a correspondence with manufacturers when necessary, should result in a significant improvement in the final sound system over that of a thrown together cabinet.

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CHAPTER VII

SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Gaining acoustic advantage over that of the human voice has been a concern since earliest times. The ancients used gongs, as well as horns of animals, to extend the natural range of signaling to others. Nineteenth century electroacoustical experiments by scientists gave impetus to the developments of an electrically driven loudspeaker, capable of reproducing sounds with some degree of fidelity, and with a greater measure of output over that of the original sound source.

Bell Laboratory's late nineteenth century developments with the electro-dynamic moving coil loudspeaker and subsequently, the permanent magnet moving coil loudspeaker, paved the way for high fidelity, high reliability loudspeaker systems to be used in theatres, recording studios, movie sound stages, and concert halls world wide. The dynamic moving coil loudspeaker has undergone relatively few major changes since the early 1930's. Modifications related to manufacturing technology, along with the development of many new types enclosures, have made it possible to achieve startlingly accurate reproduction from, compared to early days of high fidelity, what could be considered small speaker enclosures.

The initial part of this study develops the functional use for the many component parts of the loudspeaker as they relate to speaker performance as a whole. The knowledge of the working parts of the loudspeaker is necessary to the understanding of how the different parameters in loudspeaker design may be juggled to produce a speaker capable of matching a particular enclosure.

The next three chapters of this study cover the design data, loudspeaker choice, and construction tips necessary to the understanding of the three loudspeaker systems most widely manufactured today. Chapter III is devoted to the study of the variations of the basic infinite baffle speaker system. Chapter IV covers the reliable and universially accepted bass reflex enclosure system. Chapter V is concerned with the design of the ancient and most complicated of the sound re-inforcers, the horn-type enclosure. All three chapters include construction tips specific to the particular enclosure systems.

Chapter VI deals with construction data relevant to all three basic types of enclosures. Recommendations include joinery, choice of materials, bracing techniques, acoustic damping materials and techniques, wiring, and finishing data.

Finally, the appendix contains construction data tables, as well as graphic illustrations, designed to make construction of a particular enclosure system easier. The chapter also contains names and addresses of high fidelity related manufacturers where additional technical information may be obtained by the prospective builder.

Findings

As a result of this study, the following findings are presented:

1. Much supplemental information pertaining to loudspeaker systems and enclosures may be obtained through the mails from the technical service departments of the various loudspeaker manufacturers. The larger companies are the more responsive.

2. Many of the so called "new" speaker system designs currently being marketed by manufacturers are simply variations of the three major types of enclosure systems investigated in this paper.

3. It was found that a well built custom enclosure will perform as well as a manufactured enclosure.

4. It was found that the strict adherance to construction recommendations will result in noticeably improved speaker system sound quality.

5. It was found that good bracing techniques on weakened panels greatly improves the reproduction of crisp transients and low frequencies.

6. It was found that small variation in port size does not result in noticeable loss of sound quality for bass reflex systems.

7. It was found that extensive cabinetmaking experience is not a prerequisite to the completion of a functional speaker system, but accuracy and tightness of enclosure joinery are vital to the system's performance.

8. It was found that a horn-type enclosure is a most difficult project for the novice builder.

Conclusions

Based upon the findings of this study, the following conclusions are submitted.

1. It was concluded that a minimum of electronic experience was necessary to correctly build a speaker system.

2. It was concluded that technical service departments can best answer questions pertaining to the installation, wiring, and matching components of their own brand of speakers.

3. It was concluded that each type of enclosure system has its own advantages and disadvantages. The particular system the student builder chooses will produce good sound if care is taken in planning and construction.

4. It was concluded that extensive physics computations are not always necessary to design good performance into a speaker system. Nomograms and tables presented in the appendices usually yield very similar results to that of a student designed system totally computed from scratch.

5. It was concluded that the average advanced machine woodworking student has enough skills to complete a fine performing loudspeaker enclosure system.

6. It was concluded that by using a removable front baffle board for infinite baffle and bass reflex enclosures, the student builder has much more flexibility for the eventual altering or upgrading of the system.

7. It was concluded that the speaker enclosure makes a good woodworking laboratory project because the calculations and demanding joinery skills can easily be developed as steps in the completion of a goal oriented project.

Recommendations

From the results of the findings and conclusions of this study, several recommendations are submitted as follows:

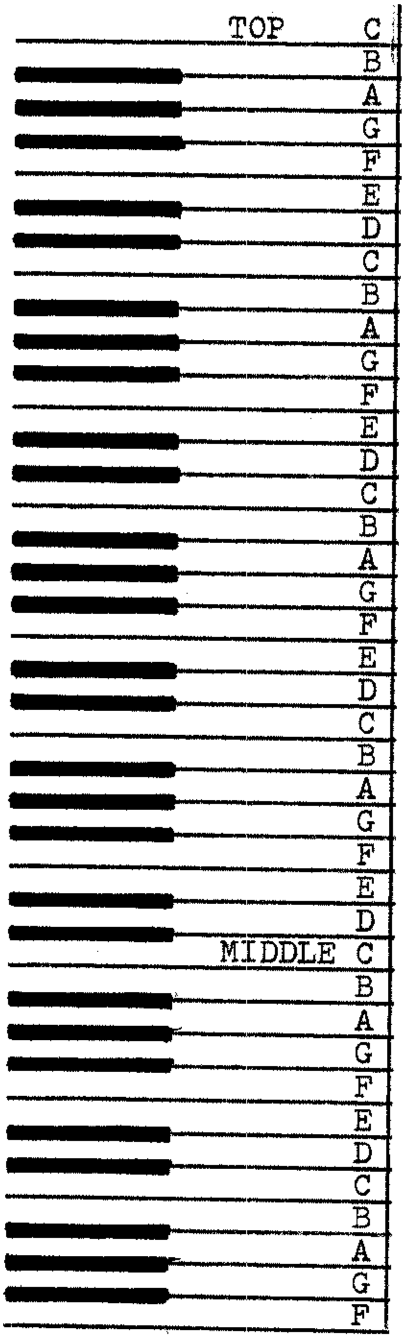
1. It is recommended that more research be done in the area of loudspeaker enclosure design.

2. It is recommended that the design and construction of enclosure systems be studied for the feasibility of developing a programmed unit for the student interested in this area of woodworking.

3. It is recommended that further study be done to define and determine the cabinetmaking skills necessary to build different types of speaker enclosures.

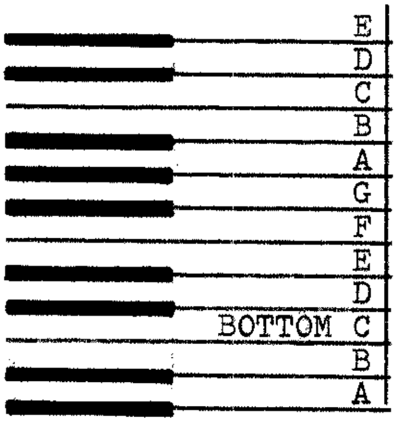
APPENDIX A

FREQUENCY-WAVE LENGTH CHART



	f	W.L.	D
TOP C	4186	3.25"	
B	3950		
A	3520	3.85"	
G	3138		
F	2794		
E	2636	5.15"	
D	2348		
C	2093		
B	1975		
A	1760	7.7 "	
G	1568		
F	1397		
E	1318		
D	1174	11.5 "	
C	1046		
B	987		
A	880	15.4 "	
G	784		
F	698		
E	659		
D	587		
C	523	2'	1'
B	494		
A	440	2.5 '	1.25'
G	392		
F	349		
E	330	3.5 '	1.75'
D	294		
MIDDLE C	261		
B	247		
A	220	5'	2.5 '
G	194		
F	174		
E	165	7'	3.5 '
D	147		
C	130		
B	123		
A	110	10'	5'
G	98		
F	87		

APPENDIX A--Continued



E	82	14'	7'
D	73		
C	65.4		
B	61.7		
A	55	20'	10'
G	49		
F	43.6		
E	41	28'	14'
D	36.7		
BOTTOM C	32.7	35'	17'
B	30.8		
A	27.5	40'	20'

f = Frequency in cycles per second.
WL = Wave length of sound (approx.).
D = Minimum diameter of baffle for speaker to reproduce down to frequency involved.

APPENDIX B

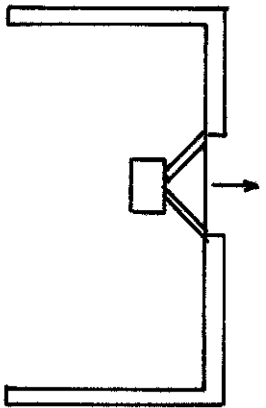
FREQUENCY RANGE OF MUSICAL INSTRUMENTS AND VOICES

INSTRUMENT	FREQUENCY RANGE OF FUNDAMENTALS
Pipe organ	16 --8,000 c/s
Piano	27.5--4,000 c/s
Harp	30 --2,500 c/s
Double Bassoon	33 -- 350 c/s
Double Bass	41 -- 380 c/s
Bass Tuba	42 -- 380 c/s
Timpani	45 c/s
Bassoon	60 -- 700 c/s
French Horn	70 -- 600 c/s
'Cello	70 -- 850 c/s
Bass Clarinet	75 -- 700 c/s
Guitar	82 -- 700 c/s
Trombone	85 -- 500 c/s
Snare Drum	80 c/s
Kettle Drum	96 c/s
Banjo	110 -- 800 c/s
Viola	150 --1,500 c/s
Clarinet	150 --1,700 c/s
Trumpet	190 -- 980 c/s
Violin	196 --3,200 c/s
Oboe	210 --1,700 c/s
Flute	300 --2,500 c/s
Cymbals	probably 350 -16,000 c/s
Piccolo	450 --3,800 c/s
HUMAN VOICE	
Bass	90 -- 300 c/s
Baritone	110 -- 400 c/s
Tenor	150 -- 500 c/s
Alto	190 -- 700 c/s
Soprano	280 --1,050 c/s

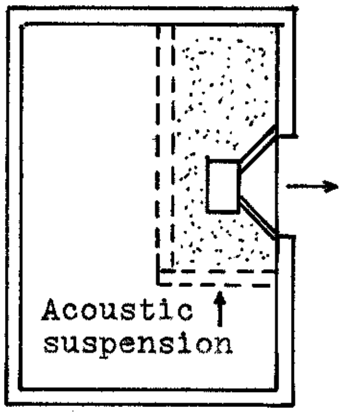
c/s = cycles per second

APPENDIX C

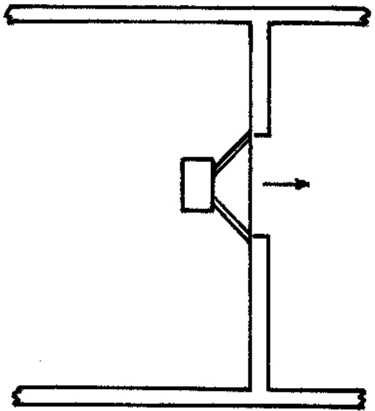
LOUDSPEAKER BAFFLES



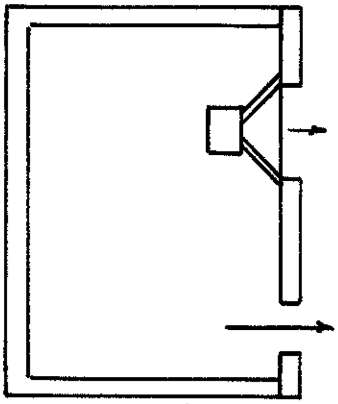
Open back baffle



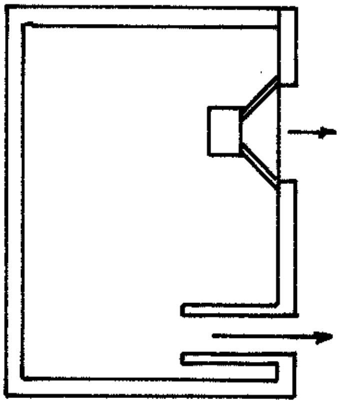
Closed baffle



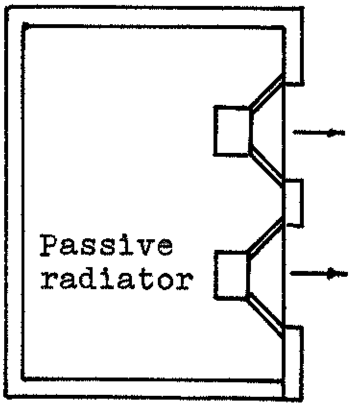
Infinite (wall) baffle



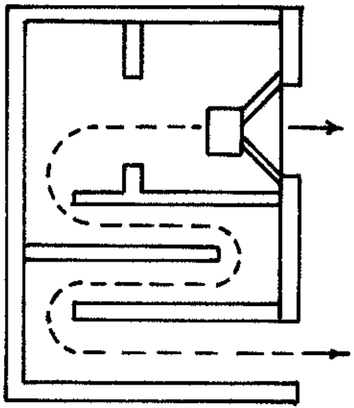
Bass reflex



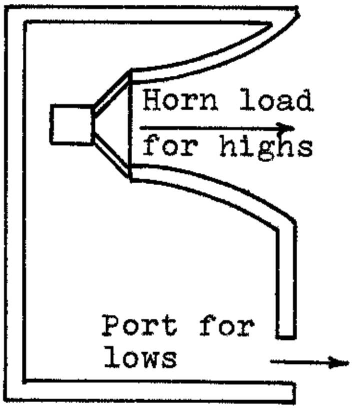
Ducted bass reflex



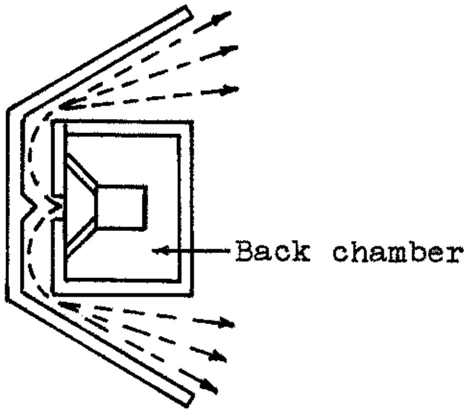
Drone cone inverter



Acoustic labyrinth
phase inverter



Combination horn-
bass reflex



Rear loaded bass
exponential horn

APPENDIX D

PORT AREA IN SQUARE INCHES (NO TUBE)

RESONANT FREQ (Hz)	CUBIC FEET					
	2.0	2.5	3.25	4.0	5.0	6.0
35						10
40				7	11	16
45				11	17	23
50		7	11	16	24	35
55	5	10	16	22	34	49
60	9	13	22	31	47	70
65	12	18	30	42	65	96
70	16	23	39	55	87	130

APPENDIX E

DUCT TUBE LENGTH OR PORT AREA REQUIRED FOR DESIRED ENCLOSURE SIZE

FREE-AIR RESONANCE	VOLUME-CUBIC FEET*				
	1.5	2.0	2.5	3.0	3.5
15	Closed	Closed	Closed	(T2) 11"	(T2) 8-3/4"
20	Closed	(T2) 8-3/4"	(T2) 6-5/8"	(T2) 5-1/4"	(T2) 4-1/2"
25	(T2) 7-1/4"	(T2) 5"	(T2) 3-3/4"	(T2) 2-3/4"	(T3) 6"
30	(T2) 4-1/2"	(T2) 3"	(T3) 5-3/4"	(T3) 4-1/2"	(T3) 3-1/2"
40	(T3) 5-1/2"	(T3) 3-1/2"	(T5) 7-3/4"	(T5) 5-3/4"	(T5) 4-1/2"
45	(T3) 3-3/4"	(T3) 2-1/4"	(T5) 5-1/2"	(T5) 3-3/4"	10 sq. in.
50	(T3) 2-1/2"	(T5) 5-1/2"	(T5) 5-1/2"	13 sq. in.	16 sq. in.
55	(T5) 6-1/4"	(T5) 4-3/4"	11 sq. in.	15 sq. in.	20 sq. in.
60	(T5) 4-3/4"	11 sq. in.	16 sq. in.	20 sq. in.	29 sq. in.
65	(T5) 3-1/4"	13 sq. in.	20 sq. in.	27 sq. in.	36 sq. in.
70	11 sq. in.	18 sq. in.	26 sq. in.	35 sq. in.	46 sq. in.
80	17 sq. in.	28 sq. in.	41 sq. in.	60 sq. in.	80 sq. in.
90	25 sq. in.	42 sq. in.	64 sq. in.	89 sq. in.	117 sq. in.
110	51 sq. in.	87 sq. in.	132 sq. in.	Closed	Closed
115	73 sq. in.	104 sq. in.	Closed	Closed	Closed

NOTE: If either the volume or resonance does not match the figures given choose the closest volume or resonance shown. If it falls halfway between, raise to the higher volume or resonance shown.

*Listed volumes are net internal volumes, exclusive of absorption material.

APPENDIX E--*Continued*

	4.0	5.0	6.0	8.0
	(T2) 7-5/8"	(T2) 5-3/4"	(T2) 4-1/2"	(T3) 8"
	(T2) 3-5/8"	(T3) 7-1/8"	(T3) 5-1/4"	(T3) 3-1/4"
	(T3) 5"	(T3) 3-1/4"	(T5) 8-3/4"	(T5) 5-1/2"
	(T5) 9-1/4"	(T5) 6-1/2"	(T5) 4-3/4"	11 sq. in.
	(T5) 3-1/4"	13 sq. in.	18 sq. in.	28 sq. in.
	13 sq. in.	20 sq. in.	26 sq. in.	43 sq. in.
	18 sq. in.	29 sq. in.	39 sq. in.	62 sq. in.
	25 sq. in.	37 sq. in.	61 sq. in.	88 sq. in.
	35 sq. in.	50 sq. in.	75 sq. in.	Closed
	45 sq. in.	69 sq. in.	Closed	Closed
	58 sq. in.	90 sq. in.	Closed	Closed
	96 sq. in.	Closed	Closed	Closed
	Closed	Closed	Closed	Closed
	Closed	Closed	Closed	Closed
	Closed	Closed	Closed	Closed

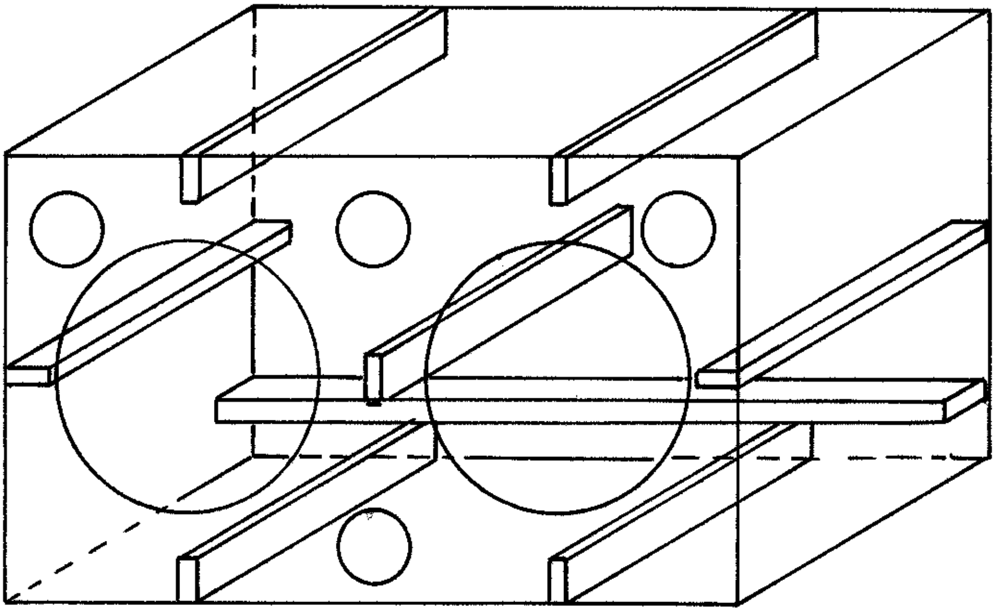
T2 = 2" I.D. x $2\frac{5}{32}$" O.D. x 12" L.

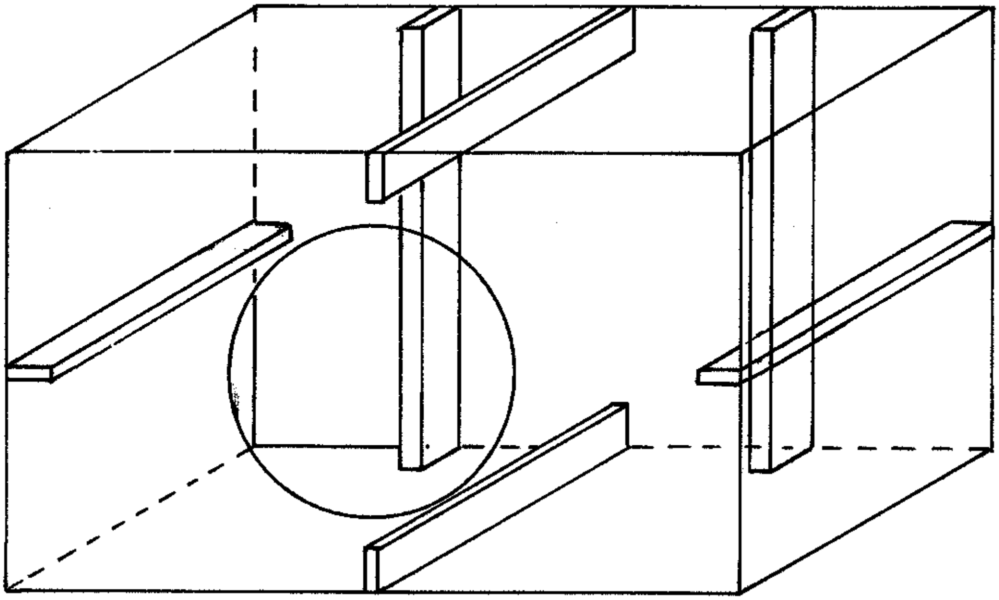
T3 = 3" I.D. x $3\frac{1}{4}$" O.D. x $7\frac{1}{8}$" L.

T5 = $4\frac{3}{4}$" I.D. x 5" O.D. x 10" L.

APPENDIX F

INTERNAL CABINET BRACING TECHNIQUES





APPENDIX G

TUBE LENGTH (INCHES) FOR A TWO-INCH DIAMETER TUBE

RESONANT FREQ. (Hz)	CUBIC FEET								
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0	6.0
20	---	---	8-3/4	6-5/8	5-3/8	4-1/4	3-5/8	2-1/2	1-7/8
25	---	7-1/8	5	3-5/8	2-7/8	2-1/8	1-5/8	1	---
30	7-5/8	4-3/8	3	2	1-1/2	1	---	---	---
35	5	2-7/8	1-3/4	1-1/8	---	---	---	---	---
40	3-1/2	1-7/8	1	---	---	---	---	---	---
45	2-1/2	1	---	---	---	---	---	---	---
50	1-5/8	---	---	---	---	---	---	---	---
55	1-1/8	---	---	---	---	---	---	---	---
60	3/4	---	---	---	---	---	---	---	---

APPENDIX H

TUBE LENGTH (INCHES) FOR A THREE-INCH DIAMETER TUBE

RESONANT FREQ. (Hz)	CUBIC FEET 1.0	1.5	2.0	2.5	3.5	4.5	6.0	8.0
20	---	---	---	---	11	8	5-1/4	3-3/8
25	---	---	---	9-5/8	6	4-1/8	2-1/2	1-3/8
30	---	11-1/2	8	5-3/4	3-1/2	2-1/8	1	---
35	---	7-7/8	5-1/4	3-1/2	1-7/8	7/8	---	---
40	9-1/4	5-3/8	3-3/8	2-1/8	3/4	---	---	---
45	6-7/8	3-3/4	2-1/4	1-1/4	---	---	---	---
50	5	2-1/2	1-1/4	---	---	---	---	---
55	3-3/4	1-5/8	---	---	---	---	---	---
60	2-3/4	1	---	---	---	---	---	---
65	2	---	---	---	---	---	---	---
70	1-1/4	---	---	---	---	---	---	---

APPENDIX I

TUBE LENGTH (INCHES) FOR A FOUR AND THREE QUARTER-INCH DIAMETER TUBE

RESONANT FREQ. (Hz)	CUBIC FEET 1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	8.0
20	---	---	---	---	---	---	---	---	11
25	---	---	---	---	---	---	11	8-7/8	5-1/2
30	---	---	---	---	---	9-1/8	6-1/2	4-7/8	2-1/2
35	---	---	---	11-1/4	9	5-5/8	3-5/8	2-3/8	7/8
40	---	---	10-7/8	7-7/8	5-7/8	3-1/2	1-7/8	7/8	---
45	---	11-3/4	7-3/4	5-3/8	3-7/8	1-7/8	3/4	---	---
50	---	8-3/4	5-1/2	3-1/2	2-3/8	3/4	---	---	---
55	---	6-1/2	3-7/8	2-1/4	1-1/4	---	---	---	---
60	9-1/4	4-3/4	2-5/8	1-1/4	---	---	---	---	---
65	7-1/4	3-1/2	1-5/8	---	---	---	---	---	---
70	5-3/4	2-1/2	3/4	---	---	---	---	---	---

APPENDIX J

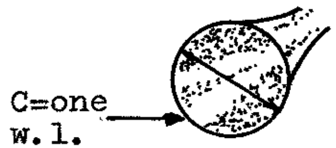
EXPONENTIAL HORN EXPANSION RATES AND MOUTH DIMENSIONS FOR VARIOUS CUTOFF FREQUENCIES

A	B	C		D	E	F
					MINIMUM CIRCULAR MOUTH DIMENSIONS	
DESIRED LOW FREQUENCY RESPONSE	THEORETICAL HORN CUTOFF FREQUENCY BASED ON COLUMN A ÷ 1.25	PERCENT INCREASE IN HORN CROSS-SECTION AREA, BASED ON COLUMN B		WAVELENGTH BASED ON 1129 ÷ (COLUMN A)	DIAMETER BASED ON MOUTH CIRCUMFERENCE OF ONE WAVELENGTH (COLUMN D ÷ π)	AREA BASED ON DIAMETER (COLUMN E)^2 $\frac{\pi}{4}$
		PER INCH	PER FOOT			
30 Hz	24 Hz	2.3%	31%	37.6 Ft.	12.0 Ft.	113 Sq. Ft.
40	32	3.1	44	28.2	9.0	63.7
50	40	3.9	58	22.6	7.2	40.8
60	48	4.7	73	18.8	6.0	28.3
70	56	5.5	89	16.1	5.1	20.5
80	64	6.3	107	14.1	4.5	15.9
90	72	7.1	128	12.5	4.0	12.6
100	80	7.9	149	11.3	3.6	10.2

See pp. 67-69 for explanation of columns A-J

(B)

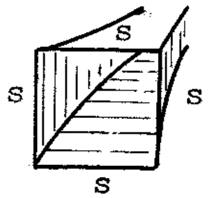
D=C ÷ (approx. $\frac{1}{3}$ dia.)



DECIMAL PARTS OF FOOT	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
APPROXIMATE EQUIVALENT INCHES	1 3/16	2 3/8	3 5/8	4 13/16	6	7 3/16	8 3/8	9 5/8	10 13/16	12

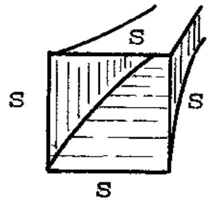
APPENDIX J--Continued

G	H	I		J	
MINIMUM SQUARE MOUTH DIMENSIONS		SQUARE MOUTH DIMENSIONS TO PROVIDE MOUTH AREA EQUAL TO THAT OF CIRCULAR MOUTH (COLUMN F)		RECTANGULAR MOUTH DIMENSIONS	
SIDE OF SQUARE BASED ON MOUTH PERIMETER = ONE WAVELENGTH (COLUMN D) ÷ 4	AREA BASED ON SIDE DIMENSION (COLUMN G)^2	SIDE	PERIMETER = 4S	MINIMUM SHORT SIDE BASED ON COLUMN G	MINIMUM LONG SIDE BASED ON AREA OF COLUMN F ÷ COLUMN J
9.4 Ft.	88.3 Sq.Ft.	10.6 Ft.	42.4 Ft.	9.4 Ft.	12.0 Ft.
7.0	49.0	8.0	32.0	7.0	9.1
5.7	32.5	6.4	25.6	5.7	7.2
4.7	22.1	5.3	21.2	4.7	6.0
4.0	16.0	4.5	18.0	4.0	5.1
3.5	12.2	4.0	16.0	3.5	4.5
3.1	9.6	3.5	14.0	3.1	4.1
2.8	7.8	3.2	12.8	2.8	3.7

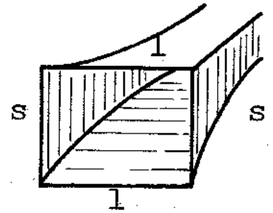


Perimeter = one wavelength

side = $\frac{\text{wavelength}}{4}$

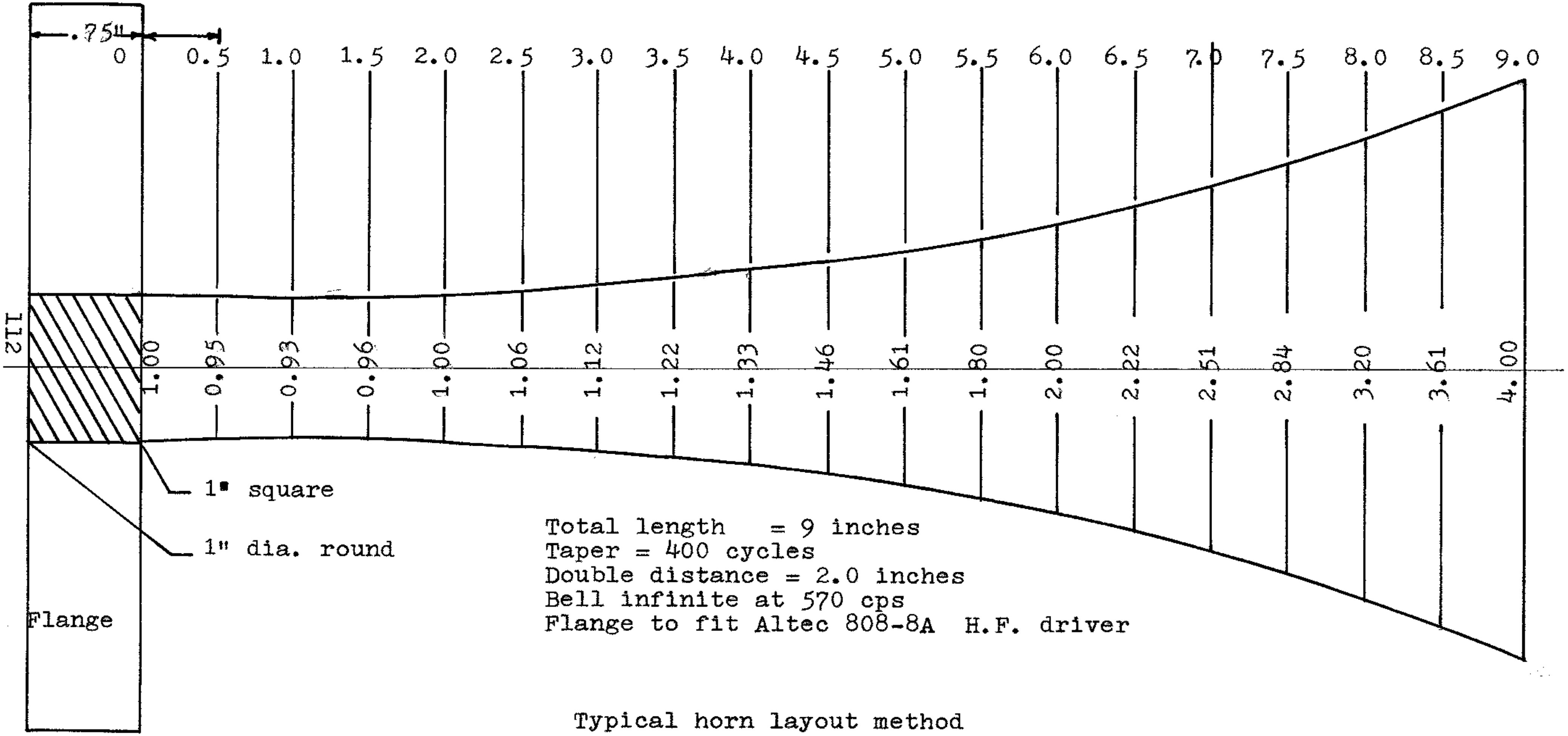


Area equal to circular area. Perimeter larger than one wavelength.



Area equal to circular area.

APPENDIX K



Total length = 9 inches
Taper = 400 cycles
Double distance = 2.0 inches
Bell infinite at 570 cps
Flange to fit Altec 808-8A H.F. driver

Typical horn layout method

APPENDIX L

SELECTED RECORDINGS FOR TESTING SPEAKER SYSTEMS

1. Also sprach Zarathustra, R. Strauss, Los Angeles Philharmonic, Mehta Conductor, London, CS 6609.
2. Ameriques, Edgar Varese, Utah Symphony, Abravanel Conductor, Vanguard Stereo, S 274.
3. An Audio Obstacle Course, Shure Test Recording, TTR 101.
4. An Audio Obstacle Course ERA III, Shure Test Recording, TTR 110.
5. Mass in C Minor, K 427, W. A. Mozart, Berlin Radio Symphony, Fricsay, Conductor, Deutsche Grammophon, 138124.
6. Missing Linc, Volume II, Lincoln Mayorga, Sheffield, S-10.
7. One Man Dog, James Taylor, Warner Brothers, BS 2660.
8. Reach Out, Burt Bachrach, A & M Records, SP 4131.
9. Switched On Bach, Walter Carlos, Columbia, MS 7194.

APPENDIX M

LIST OF SPEAKER MANUFACTURERS

1. Acoustic Research Inc.
   24 Thorndike St. Cambridge, Massachusetts 02141
2. Altec Lansing Corp. (division of LTV Aerospace)
   1515 S. Manchester Ave. Anaheim, California 92803
3. Bose Corp.
   East Natic Industrial Park, Natic, Massachusetts 01760
4. Bozak Manufacturing Co.
   Box 1166 Darien, Connecticut 06821
5. Crown International
   P. O. Box 1000 Elkhart, Indiana 46514
6. CTS of Paducah, Inc.
   1565 North 8th St., Paducah, Kentucky 42001
7. Electrovoice Inc.
   649 Cecil St. Buchannan, Michigan 49107
8. Elite Electronics
   195 Central Ave. Farmingdale, New York 11735
9. Frasier Inc.
   1930 Valley View Lane Dallas, Texas 75234
10. Hartley Products Corp.
    P. O. Box 68A Ho-Ho-Kus, New Jersey 07423
11. James B. Lansing Corp.
    3249 Casitas Ave. Los Angeles, California 90039
12. Jensen Manufacturing Co.
    5655 West 73rd St. Chicago, Illinois 60638
13. Karlson Research Corp.
    P. O. Box 117 West Hemsted, L.I., New York 11552
14. KLH Research Corp.
    30 Cross St. Cambridge, Massachusetts 02139

APPENDIX M--*Continued*

15. LWE Acoustron Corp.
    2418 Bartlett, Houston, Texas 77006
16. Paul G. Klipsch and Associates
    P. O. Box 280 Hope, Arkansas 71801
17. Toby Corp. of America
    4620 Camp Bowie Fort Worth, Texas 76107
18. University Sound
    P. O. Box 26105 Oklahoma City, Oklahoma 73126
19. Utah Loudspeakers Inc.
    Huntington, Indiana

APPENDIX N

LETTER TO TECHNICAL SERVICE DEPARTMENT REQUESTING INFORMATION

3425 Avenue N
Plano, Texas 75074
July 1, 1970

James B. Lansing Sound Inc.
Technical Service Department
3249 Casitas Avenue
Los Angeles, California 90039

Dear Sir:

I am presently engaged in a thesis study involving the construction of different types Hi-Fi loudspeaker enclosures. I would be very appreciative of any resource material you might be able to send me.

I am interested in speaker construction, speaker enclosure matching, physics, acoustics, and construction techniques of enclosures (primarily infinite, bass reflex, and horn, but any others would be valuable). If remittance is necessary, I would be happy to do so.

Thank you,

Steve Allen
Industrial Arts Dept.
North Texas State Univ.

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