Design and Construction of Horn-type Loudspeakers

WAYNE B. DENNY*

Part I. In the never ending search for good clean bass, builders are turning more and more to the exponential horn—not admirably suited to furniture designs. The two presented by the author should be pleasing, both acoustically and aesthetically.

NUMEROUS REQUESTS for information about a speaker described by the writer in a previous article[1] have indicated that there are many audio enthusiasts who would like to construct horn speakers for their own use but who hesitate to do so without a better understanding of the theoretical and practical considerations which must be taken into account if results are to be satisfactory. Actually, there is nothing mysterious or esoteric about the design and construction of horn-type loudspeakers. The design of a satisfactory unit requires no great mathematical ability. The construction requires no more than a minimum of woodworking ability as far as acoustical performance is concerned. Of course, if appearance is a factor, the skills of a cabinetmaker may be employed for the visible part of the structure.

Theoretical Considerations

The acoustic horn can best be thought of as a transformer which accepts sound energy at its throat and delivers that same energy in somewhat different form at the mouth of the horn. The motion of the air in the constricted portion of the horn near the throat is characterized by relatively high velocity and displacement amplitudes. However, the amount, or mass, of air which moves in this manner is small because the cross-sectional area of the horn is small near the throat. In contrast to the motion of the air in the throat, the motion of the air at the mouth of the horn is characterized by relatively low velocity and displacement amplitudes but the mass of air moving in this region is much larger. An analogy is often made between the acoustic horn and the *impedance changing properties* of an electrical transformer. Thus, for example, a step-up transformer accepts electrical energy at high current and low voltage and delivers that same energy (minus losses, of course) at low current and high voltage. The fundamental purpose of the acoustic horn is to match the impedance of the cone or diaphragm of the driving unit to the impedance of the space into which the sound is to be propagated.

This analogy may be carried a bit further. A good audio frequency transformer must be designed so that its frequency characteristic is essentially flat over the entire audible range. An ideal horn would have a similar frequency characteristic. Electrical transformers are now available which are nearly perfect in this respect but it is found that it is difficult to cover the entire audible spectrum with a single horn if total space occupied by the horn is to be kept within acceptable limits. The physical shape is another factor which must be considered in the design of a practical horn. For these and other reasons it is convenient to use two or more separate horns, each one designed to cover but a portion of the audible spectrum.

The two design factors to be considered are shape and size. The shape will be considered first. Theory and experience[2] indicate that the most satisfactory shape is the so-called exponential horn. An exponential horn is best defined as one which obeys the following equation:

$$A_2 = A_1 \varepsilon^{kx} \qquad (1)$$

where A_1 = cross-sectional area at any point in the horn

A_2 = cross-sectional area at a distance x from the point where A_1 is measured. ($A_2 > A_1$)

k = flare constant

$\varepsilon = 2.718$, the base of natural logarithms

The application of this equation is shown in *Fig.* 1.

For design purposes it is convenient to let $\frac{A_2}{A_1} = \varepsilon^{kx} = 2$. From a table of exponentials

$$kx_d = 0.7 \qquad (2)$$

In Eq. (*2*), x_d represents the particular increment of horn length in which the area doubles. For a true exponential horn the area doubles for this increment of length no matter what particular value is chosen for A_1 (or A_2).

The value chosen for x_d depends on the lowest frequency for which the horn is to be used. This is called the cut-off frequency, f_c, where

$$4\pi f_c = kc \qquad (3)$$

where c = velocity of propagation of sound in air (about 13,200 inches/second)

After f_c is chosen, k may be determined from Eq. (*3*) and then x_d may be found from Eq. (*2*).

Example: Let $f_c = 40$ cps

Then $k = \frac{4\pi \times 40}{13{,}200} = .038$

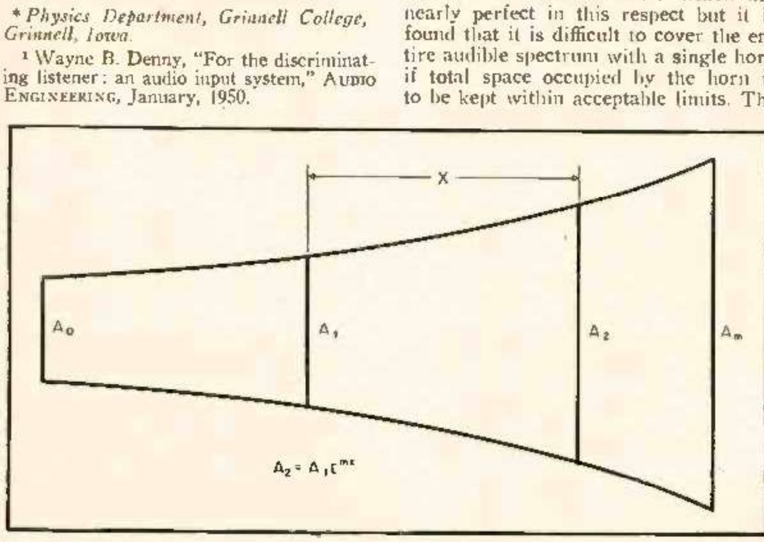

Fig. 1. The rate of expansion of an exponential horn, related to its mathematical expression.

* *Physics Department, Grinnell College, Grinnell, Iowa.*

[1] Wayne B. Denny, "For the discriminating listener: an audio input system," AUDIO ENGINEERING, January, 1950.

[2] Lawrence E. Kinsler and Austin R. Frey, *Fundamentals of Acoustics*. New York: John Wiley and Sons, Inc., 1950. Ch. 11.

HORN-TYPE LOUDSPEAKERS

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tions with consequent resonances and standing waves. The problem, then, is to *reduce* the magnitude of these resonances to a small value. They cannot be entirely *eliminated* because no horn of practical size can effect a perfect impedance match with the interior of the usual room.

Fortunately, this problem is not quite so serious as it seems. Most horns are used in rooms which themselves exhibit several resonant modes of vibration. The standing waves which result from room resonance are not ordinarily considered objectionable. Actually, horn resonances can be reduced to the point where they are masked by room resonances. When this is done the results are superior to those obtained from loudspeakers without horn loading.

There are three practical ways in which the effects of horn resonances can be reduced in loudspeaker systems. First, the horn structure can be made as large as practicable. Second, two or more rates of flare can be used in different sections of the horn. Third, the horn can be placed in the corner of the room so that the floor and walls will form a virtual horn which extends into the room itself. The last expedient is very effective in increasing the virtual mouth area. In most cases it provides the best possible impedance match between the generator (driver) and load (room).

Practical Considerations

The foregoing paragraphs have shown the most important theoretical considerations which govern the performance of horn-type loudspeakers *once the several design constants have been chosen.* However, it is usually impossible to assign numerical values to the design constants on the basis of theory alone. A loudspeaker is, among other things, an article of furniture and practical considerations of size and appearance must be taken into account as well as acoustical performance. Sometimes compromises must be made in order to fit equipment into available space. It is the purpose of this section to discuss the practical construction of horn speakers. This can best be done by describing the constructional features of two horn speakers built by the writer for which data are available. The two examples chosen for description are quite different in conception and will serve to illustrate the major requirements which must be met in any system. One of these horns is described in the following paragraphs, and the other follows next month.

Several years ago Olson and Massa[3]

[3] Harry Olson and Frank Massa, *J. Acous. Soc. Am.* Vol. 8, No. 1, p. 48, 1936.
Harry Olson, *"Elements of Acoustical Engineering,"* 2nd ed., Van Nostrand, New York, 1947.

described in the literature a loudspeaker employing two horns and one motor. The low-frequency horn was coupled to the rear of the cone and the middle- and upper-frequency horn was coupled to the front of the cone. Later there appeared in the literature a description of the now familiar Klipsch horn which employed the corner of the room in order to extend the dimensions of the virtual horn. The speaker to be described is a modification of the Olson-Massa design and incorporates the room-corner feature. Although the speaker was built several years ago its performance is still considered excellent. It compares favorably with more recent designs which are vastly more expensive. Using the writer's speaker as a prototype, other constructors have built similar units and have reported excellent results.

Figure 2 shows the main constructional features. The eight-inch cone is mounted near the top, secured to a vertical mounting board about half way back from the front of the structure. A short horn extends forward from the cone. Behind the speaker mounting board is the speaker chamber. The low-frequency horn connects to the lower portion of the speaker chamber and the mouth of the horn is at the front of the structure near the bottom.

For the sake of clarity some of the details are omitted from *Fig. 2* and are shown in *Fig. 3*. (A) in *Fig. 3* shows

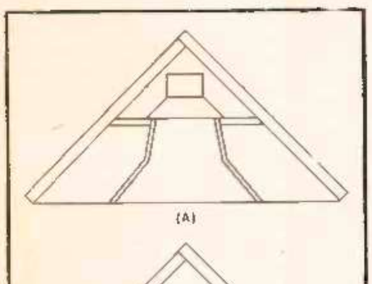

Fig. 3. Details of top (A), center (B), and bottom (C) sections of the duplex-horn speaker.

the plan of the top section of the structure. This section includes the cone, the high-frequency horn, and the upper part of the chamber. (B) shows the plan view of the center section which comprises the lower part of the chamber, the throat and part of the low-frequency horn. (C) shows the lower section of the structure, comprising the remainder of the low-frequency horn.

The functions of the various partitions can best be explained by tracing the path of the low-frequency horn. As shown in (B) of *Fig.* 3, the throat is in two parts: one half is at *a*, the other at *c*. The first portion of the horn consists of two parallel paths, from *a* to *b* and from *c* to *b*. The paths converge at *b* and immediately pass down into the bottom section through the hole at *b*. The horn then splits into two parallel paths, each of which opens separately at the front of the bottom section, as at (C) of *Fig.* 3.

The effective length of the low-frequency horn is about 45 inches. The total mouth area is about 360 square inches and the total throat area is about 38 square inches. Considerable liberty was taken in the rate of flare in the interest of simpler construction. However, the average rate of flare provides for a theoretical low frequency cut-off at about 52 cps. Eqs. (*1*) and (*3*). This should not be taken too seriously, however, since finite horns radiate appreciable energy at frequencies less than cut-off. This particular speaker, for example, produced fundamentals of 16 cps with considerable intensity. This was the lowest frequency available from the test oscillator. (No claim is made for "flat" frequency response at these low frequencies.)

Interference Effects

It was mentioned earlier that a folded horn does not radiate efficiently at higher frequencies where interference effects exist because of differences in path length. For this reason, the upper limit of the low-frequency horn should be determined before the other horn is designed and built. There is no simple way to compute what this upper limit is: it must be measured after the horn is in operation. A convenient method is to block off the radiation from the front of the cone with absorbing material (pillows, blankets, etc.) and check the operation of the low-frequency horn with an oscillator connected to the driver. Once the approximate upper frequency is determined, the high-frequency horn can be designed to complement the characteristics of the larger horn.

The two vertical boards which comprise the outside "vee," *Fig.* 3 are cut from ¾-in. plywood. The speaker mounting board is made of ½-in. plywood. All other partitions are ¼-in. plywood. All joints are nailed, glued, and reinforced with cleats. A portion of the top is secured by screws to permit access to the cone. The resulting structure is very sturdy. The inside horn surfaces were given several coats of thin shellac and sanded between coats. The resulting surface is very hard. The internal damping of the wood partitions is sufficient to eliminate all but a trace of vibration.

Experiments on this and other units have demonstrated conclusively that the use of thicker wood is no guarantee of reduced horn vibration. One speaker similar to the one described here was built of ¾-in. wood throughout. The vibrations of the horn walls were much more intense for the same electrical input signal. It was necessary to install heavy braces between partitions, and still the braces vibrated. Only by bracing the braces was the problem solved. A clue to the reason came when it was observed that the resonant frequencies of thick partitions were higher than those for the thinner vibrations, other factors being the same. Now, the rigorous theory of vibrating plates is highly complicated but a simpler explanation appears plausible. Consider the following equation for the natural frequency of a simple oscillator:

$$f = \frac{1}{2\pi}\sqrt{\frac{s}{m}} \qquad (5)$$

where m = mass of the vibrating body
s = stiffness factor

In this case the "stiffness" is the reaction of the wood to bending. If we double the thickness of the wood the mass of the body is doubled. However the stiffness of the wood increases much more rapidly than the mass. Consequently, the natural frequency increases: it does not decrease as might be expected. The only advantage gained by increasing the thickness of the wod is the consequent increase in mechanical resistance. Apparently, this advantage is sometimes outweighed by the increase in the resonant frequency *if* this shift means that the resonant frequency is raised from a sub-audible to a value which causes poor transient response in the audible range. It appears

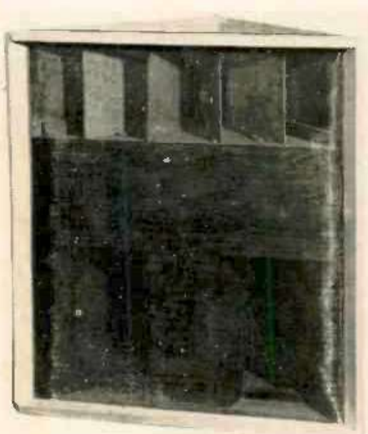

Fig. 4. The completed duplex-horn speaker. Barely visible is the protecting screen which hides the mechanism under normal illumination.

that the most effective way to damp out horn vibrations is to use relatively thin wood and to coat the outside of the horn with viscous damping material to lower the "Q" of the vibrating element.

The only difficulty experienced with this speaker when first constructed along the lines indicated by *Figs.* 2 and 3 was undesired cavity resonance of the Helmholtz type in the speaker chamber. This trouble was effectively eliminated by decreasing the volume of the chamber below that shown in the diagrams. One simple way of doing this is to fill part of this space with sound absorbing material. Another is to block off part of

Fig. 5. Speaker chamber in the top section. The plywood partition below the speaker magnet indicates the reduction in chamber volume which was required to reduce cavity resonance.

the chamber by the use of additional partitions. The writer employed the second alternative, as shown in *Fig.* 5.

The front of the completed unit can be covered by a grill to improve the appearance. *Figure* 4 shows a wood frame with bronze screening attached. Thick fabric should not be used, particularly in front of the high-frequency horn because it offers appreciable resistance at the higher frequencies, but Lumite plastic grill cloth may be considered satisfactory. The high-frequency horn shown in *Fig.* 4 is somewhat different from that shown in the diagrams of *Figs.* 2 and 3. The model shown in the photograph employs a three-section horn. The two additional partitions were found desirable to increase the dispersion at middle and higher frequencies.

One variation of this design which was brought to the writer's attention deserves mention. It uses a conventional two way speaker with concentric tweeter in place of the single cone specified. Thus, no high frequency horn need be constructed. Reports indicate that excellent performance is obtained in this manner. Since most two-way speakers use large low-frequency cones the total length of the low-frequency horn is lowered for the same mouth area. For dual speakers with relatively high crossover frequencies the action is threefold. The large horn is effective only at the lower frequencies, the middle range is taken from the front of the cone, and the "highs" are obtained from the tweeter.

The second type of horn for low-frequency radiation is a vertical corner-cabinet model which can be accommodated in the average home without too great a domestic upheaval—provided the cabinet-making abilities of the builder will satisfy the distaff department. This model will be described next month in Part II of this paper.

TECHNICANA

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nism which turns the equipment on and provides for a warm-up period needed for the amplifiers. In addition to the clock are a set of tubular chimes, striking mechanism, motor drive timing unit, contact discs, timing discs, and cam discs. The three sets of discs provide for the appropriate sequence at correct intervals with such random variation in timing and sound as are peculiar to hand ringing.

The unit may be installed remote from the bell tower with several remote switch positions for sounding bell sequences, and clock control of the Angelus sequence. The accuracy of the unit is plus or minus two minutes which was adequate for the application. Greater accuracy may be obtained, however, using other types of clocks. The one in this unit is a spring driven clock with a rundown time of thirty-six hours, the motor being electrically rewound every eight hours. The size of the dial is three inches. A synchronous clock with standby power would be the next step in improving the performance.

Music-Speech Level Ratios

Results of the BBC tests on switching between speech and music were published in *Wireless World*, December 1950. The tests included engineers, musicians, and the public. Also the tests were used to determine the preferred maximum sound level at which the various groups liked to listen. This was done in order to establish the change in equalization need between the monitor speaker channel and the program channel. Table I shows the preferred levels and Table II the preferred change in level between program material of various types.

Finally, $x_d = \frac{0.7}{0.038} = 18$ inches, approximately.

Therefore the cross sectional area of an exponential horn should double every 18 inches in order to reproduce frequencies as low as 40 cps.

Other Considerations

There are three other considerations about horn shapes that should be mentioned. The first has to do with slight deviations from the exact rate of flare chosen. Experience indicates that for high-frequency horns (tweeters) the shape of the horn should conform as nearly as possible to the design criteria. Since high-frequency horns are small, this requirement presents no great problem. For low-frequency horns (woofers) considerable latitude seems permissible provided that the deviations are small compared with the shortest wavelengths to be used. Actually, there is some advantage in making a low-frequency horn with different rates of flare in different portions of its length. However, such deviations should be gradual and not abrupt.

Another factor in the shape of the horn is the effect of folds or bends. At the lower frequencies there is little difference between a straight horn and a folded horn because differences in path length in different parts of the horn are small compared to the wavelength. At higher frequencies, however, this is not true. Different portions of the wave travel different distances from the throat to the mouth of the horn and trouble occurs when this difference in path length approaches or exceeds one half wavelength. Under this condition it may be expected that there will be marked irregularities in the frequency response and in the directional characteristics of the horn. It is convenient, therefore, to use long, folded horns for the reproduction of low frequencies and to use short straight horns for the reproduction of the middle and higher frequencies. The situation can be summarized by saying that a folded horn has an upper limit to its frequency response as well as a low-frequency cut-off.

There are certain things that should be avoided in the design of folded horns even when they are to be used exclusively at low frequencies. In no case should the shape of the horn be favorable to the generation of standing waves, which are likely to occur whenever there is opportunity for sound waves to bounce back and forth between two parallel surfaces. This type of resonance can be avoided by taking into account the laws of reflection.

The last factor which should be considered about the shape of the horn is the shape of the cross-section. Horns need not be circular. They can be square, rectangular, or triangular. Different sections of the horn can have quite different cross-sections. However, the design should avoid abrupt changes: changes should be gradual throughout the length of the horn.

The question of horn size will be considered next. The throat area, A_0, is determined primarily by the design of the motor which drives the horn. However, no attempt should be made to deliver very large amounts of acoustic power into a small throat area. Under such conditions the variations in air pressure may approach the ambient pressure of the air and serious distortion can result. This is because the elastic properties of air are non-linear except for small amplitudes. Fortunately, for most applications this is not a design limitation. It is convenient, therefore, to give the throat an area whose value is somewhat less that the area of the cone for horns driven by conventional dynamic reproducers. In the case of tweeters the throat area is determined by the size of the coupler attached to the high frequency driver.

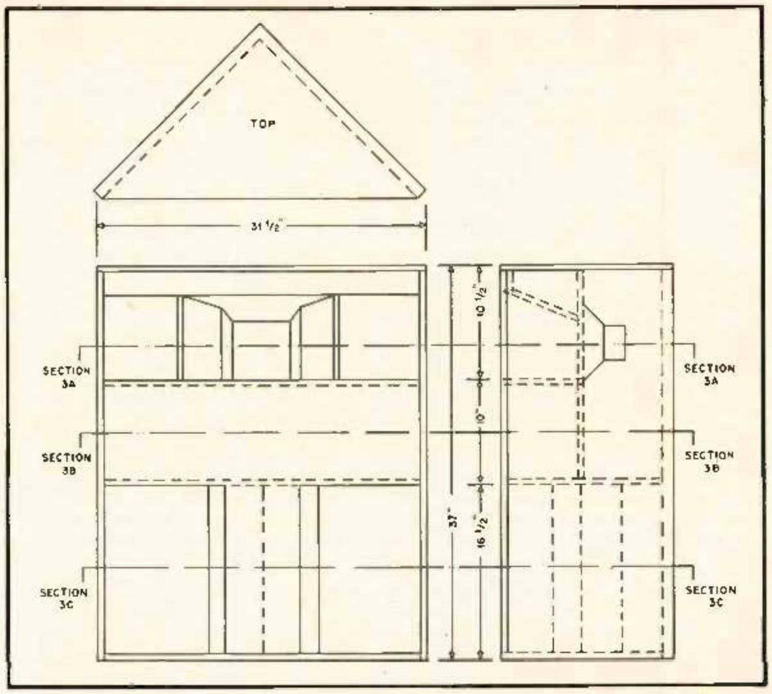

Fig. 2. Elevation of the corner speaker with duplex horn, with basic dimensions.

Next, the mouth area, A_M, must be determined on the basis of the lowest frequency which it is desired to reproduce. It is erroneous to conclude from Eq. (*3*) that the lowest frequency depends solely on the rate of flare. This is because, strictly speaking, Eq. (*3*) applies only to horns which are infinitely long and which have, as a direct consequence, infinitely large mouth apertures. A short review of some elementary acoustical theory will show the importance of the size of the mouth area.

Rate of Flare

According to Eq. (*3*) the less the rate of flare, the lower is k. To take an extreme case, k might be made zero in the hope that the horn will respond to extremely low frequencies. Then, according to Eq. (*1*), the horn degenerates into a tube of uniform cross section. But, as every physics student knows, a long open tube does *not* respond equally to all frequencies. Rather, it exhibits strong resonances at those frequencies for which the length of the tube is

$$l = n\left(\frac{\lambda}{2}\right)$$

where $n = 1, 2, 3, 4$, etc.
and λ = the wavelength = c/f

Eq. (*4*) represents the condition for standing waves which are the resultant of two similar waves moving in *opposite* directions in the tube. The forward wave is the desired mode of propagation while the backward wave is produced by reflections which occur at the open end of the tube. In general, reflections occur wherever there exists a discontinuity in the air column unless the wavelength is very small compared with the diameter of the tube. For a uniform tube, reflections occur at the open end where the cross-sectional area changes abruptly from a small finite value to a large (quasi-infinite) value.

A long acoustic tube may be thought of as an acoustic transmission line with its own characteristic impedance. It is an elementary fact about finite transmission lines—be they acoustic or electric—that reflections will occur at the end of the line *unless the line is terminated in its own characteristic impedance.* The difference between the tube and the horn is this: the impedance of the tube is constant throughout its length while the impedance of the horn (due to its "transformer action" which has already been mentioned) varies throughout its length. At certain frequencies where the wavelength is not small compared with the dimensions of the mouth, the horn will exhibit reflec-

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