Horn-Type Loudspeakers

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Design and applications of these speakers.

PRACTICALLY all of us are familiar with the exceptional distance covered by horn-type loudspeakers. Because of their high sound output they are generally associated with outdoor installations. Horn-type loudspeakers are invariably more efficient than cone-type speakers. The directional characteristics further intensify the sound on the horn axis.

While most sound and radio technicians are familiar with the design and principles of cone type speakers, the horn or indirect radiator, as it is sometimes called, is usually taken for granted without true appreciation of its characteristics. Most technicians also know that the horn loudspeaker does not appear to have the fidelity of a properly baffled cone speaker. Where the horn type speaker is apparently lacking in low frequencies, such a lack is not inherent in the principles and is only missing because of compromise with the physical size of the horn, since the low-frequency capabilities of the horn are determined by the length of the air column and diameter of the mouth. The larger the horn, the better its low-frequency efficiency. The limit to the size of a horn projector is generally dictated by physical adaptation to the installation. But given unlimited size, a horn-type loudspeaker will surpass our best cone speakers in efficiency, flatness of response and frequency range.

Horns are associated with loudspeaking units, commonly known as driver units. The diaphragm of a driver unit is small compared to a conventional cone speaker, but this does not necessarily have much bearing on the low-frequency capabilities. The diaphragm of a driver unit is generally between two and three inches in diameter where it acts as a piston. Such a small area cannot act directly on the atmosphere without a horn because of the poor low-frequency coupling to the atmosphere. A horn is necessary so that the driver unit is uniformly matched to the atmosphere for all frequencies through the desired transmission range. Looked at in the light, a horn may be regarded as a transformer which matches the acoustic impedance of the driver unit to the surrounding air.

Function

Early literature and patents frequently referred to horns as amplifiers or resonators. They are certainly not amplifiers, and the existence of resonances would be fatal to good reproduction. Their function is to cause the driver unit to operate at its maximum efficiency.

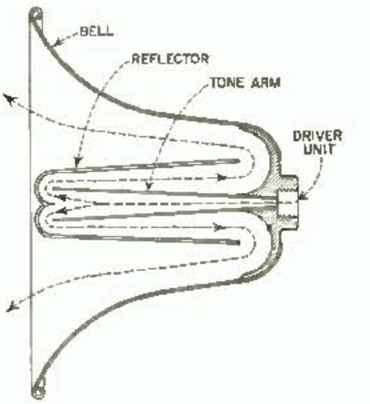

Fig. 1. Typical reflex horn consisting of three sections. Commonly available with air column lengths from one to seven feet. Dotted lines indicate sound-path. Physical length is roughly ⅓ air column length.

The small end of the horn has an acoustic impedance equal to the diaphragm, while the large end possesses approximately atmospheric pressure. Uniform high radiation efficiency demands that the horn have a constant impedance at all frequencies through the audio band it is to cover. The driver unit is an "indirect" radiator because the diaphragm is incapable of delivering sound energy to the atmosphere with any efficiency.

The diaphragm works with a very small load if uncoupled from a horn. Its own natural resonance frequency will be pronounced and the useful work performed by the diaphragm on the air will be very small. The low frequencies will be completely absent. If a driver unit is excited without a horn, the diaphragm experiences extreme excursions and the amplitude may be so great as to cause it to strike the sound head or pole piece. Yet with this great diaphragm movement, there is negligible useful sound.

A horn is, in effect, a high-pass filter. The point at which it starts to pass is its "cutoff frequency," and is determined by the flare of the horn. A very low cutoff means a slow rate of expansion, terminating in a mouth diameter which must be at least 1/3rd of the actual wavelength of the sound at its cutoff frequency; thus it follows that a real low-frequency horn must be a large one.

Design

The design of a horn must provide a constant loading at the throat (small end) in order that the response may be uniform. If this loading or damping force is irregular with frequency, the final sound output will be irregular. Such non-uniform loading may be caused by an imperfect rate of flare, and gives rise to reflections within the horn, reacting in turn upon the diaphragm. Such conditions show up as dips in the response curve which might otherwise be flat. But a carefully designed and executed horn, when coupled to a proper driver unit, will have a flatter output than is obtainable from any other type of electro-mechanical transducer. It can be commercially held within plus or minus 2 db within its band pass range, whereas the best cone speaker will vary by plus or minus 5 db and when installed in a cabinet, the latter will be further characterized by hundreds of pinpoints of cancellations caused by reflections of the rear wave. The so-called reflexed cabinet may further contribute to low-frequency non-linearity by putting a whopper of a dip at the frequency where the rear wave is out of phase with the front wave at the port position.

A horn may be considered as a wave

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guide which is energized by the diaphragm of a driver unit, and has such shape whereby the flow of energy through the guide and into the air is not influenced by conditions giving rise to wave reflections. The requirements for high radiation efficiency demand that the horn have a constant impedance at all frequencies above its specified cutoff.

The frequency which is equal to

$$\frac{M \text{ (flare factor)} \times \text{Velocity of sound in air}}{2\pi}$$

is the critical cutoff frequency for the functioning of the horn. The horn does not radiate at or below this frequency. Its characteristic as a high pass filter is quite marked. The larger the value of M (rate of flare), the more rapid does the horn diameter expand, and the critical frequency occurs at higher values.

The particular low-frequency desired determines the major design considerations. This resolves itself into two factors. First, the flare characteristics of the horn (which may be regarded as part of an infinitely extended wave transmission line, [the impedance of which varies according to mathematical law) and secondly, the radiating properties of the mouth. Considering now the first factor, the cut-off is built into the taper so that the cross-sectional area of the horn varies according to exponential law with the distance along the sound axis. The exponential factor M is known as the "rate of flare" and is equal to the percentage increase in area per unit length along the axis. A property of a finite exponential horn is that its transmission range is inherently limited at the low frequency end, such range terminating at the cutoff frequency. This low-frequency limit is obtained from the equation:

$$\text{Frequency of cutoff} = \frac{MC}{4\pi}$$

Where M = Flare factor
C = Velocity of sound in air in cm. per sec.

Coöperating with the rate of flare is the area of the horn mouth, and this becomes critical near the cutoff frequency. At frequencies close to cutoff the horn mouth is called upon to maintain constant impedance and radiating efficiency into free air. There must be a minimum of reflection at the horn mouth. This is achieved if the diameter is approximately 1/3rd the length of the wave of the cutoff frequency for which the flare taper was selected. For example, if we desired a horn with a cutoff at 100 c.p.s. the flare must be such as to increase by 40% in area with each foot of air column length. This results in an exponentially sloping column which is continued until a diameter is reached meeting the following equation:

$$Dm = \frac{V}{3\,Fco}$$

Where Dm = required mouth diameter in feet.
V = velocity of sound in air (approx. 1150) ft. per sec.
Fco = cutoff frequency. (c.p.s.)

$$Dm = \frac{1150}{300} = 3.83 \text{ ft.}$$

Air vibration of the upper frequencies leave the horn mouth with roughly plane wave fronts, but tend to bend more as the frequency becomes lower. As cutoff is reached, the emitted wave is widely diffracted and the throat impedance undergoes wide changes as serious longitudinal reflections take place within the horn.

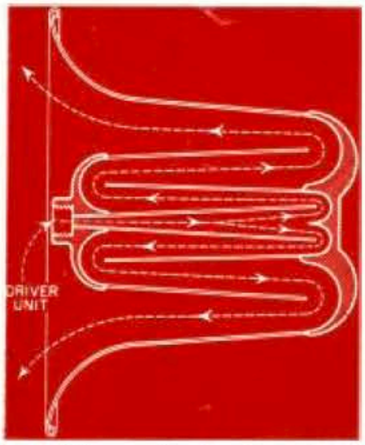


Fig. 2. A four-section reflexed horn. Dotted lines indicate sound-path. Physical length is roughly ¼ air column length. Not very common but would be employed for exceptionally long air columns for low frequency reproduction.

In practical production, most of the cost of a horn is contained in the material which forms the mouth, especially toward the rim. For this reason, practically all the manufacturers terminate in a mouth diameter which is considerably less than the one-third wavelength called for by the rate of flare. The mouth diameters of all horns available today follow a one-quarter or less rule. This disparity between flare rate and mouth diameter raises the cut-off frequency and places one or more dips or steps in the normal low frequency roll-off, demonstrating erratic loading in the cut-off region.

Conical Horns

Conical horns with linearly sloping walls have been used, and in these the increase of diameter from throat to mouth takes place by *equal amounts* per unit length along the sound axis. Calculations and tests have proven that a finite conical horn is inferior to an exponential horn in the low frequency range. However, a reasonable compromise is obtained when two-thirds of the horn is conical, and the final third (toward the mouth) has an exponential flare.

An exponential horn is one in which there is a constant *percentage increase* in area per unit length. In an exponential horn, the area at a distance X from the throat is given by the equation:

$$A_2 = A_1 \times 2.718^{MX}$$

Where A_1 = area at throat
A_2 = desired area at distance X
M = flare constant

When the factors for the conical and exponential horns are plotted, it is found that above the cutoff frequency the exponential horn rapidly reaches its ultimate resistance, whereas a conical horn does so very gradually. The superiority of the exponential horn lies in this fact. Actually, to speak of "cutoff" in a conical horn of normal length is fallacious because there is no sharply defined frequency at which the acoustic resistance undergoes a sharp discontinuity. However, manufacturers of reflex or folded horns are tending to employ conical sections for the small diameter, or inner, members of the horn, because these can be economically fabricated on metal cutting or bending machines and lend themselves to mass production. Exponential sections must be individually spun on a spinning lathe, either from tubing or a disc of metal, and their production is relatively slower. The outer member, forming the bell or mouth must have an exponential flare and is therefore spun to shape.

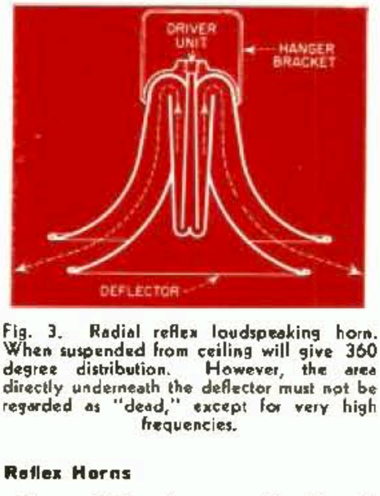


Fig. 3. Radial reflex loudspeaking horn. When suspended from ceiling will give 360 degree distribution. However, the area directly underneath the deflector must not be regarded as "dead," except for very high frequencies.

Reflex Horns

From all the above considerations it is apparent that a long air column with a wide mouth is required to transmit efficiently down to a substantial low value. However, such great lengths are awkward and difficult to handle. Skilled design has reduced the physical length of horns, without reducing the air column, by folding such horns. The reflex horn is quite old in conception, but unfounded prejudices against their efficiency withheld their appearance on the market until about ten years ago. Many reflex forms have been shown, but the one in common use today is that in which the sound conduit is re-entrantly folded twice. That is, the horn is internally folded so that the air column reverses itself by 180 degrees twice. Thus the physical length of the horn is approximately 1/3 the air column length. The popular reflex horns today have a flowerlike appearance, containing in their center what may resemble the flower's pistil.

As shown in *Fig. 1*, the reflex horn contains essentially three sections, the innermost which connects acoustically with the driver unit, is known as the "tone arm." Surrounding this is the center member called the "reflector," and the final and largest member is the "bell." Each section is tapered to give the degree of expansion required to provide the desired cutoff. Generally, the *rate of expansion* is uniform for all three members, but this may be varied in minor extent for each section in order to modify the throat impedance characteristic. However, with a correctly designed driver unit, it is preferable to maintain uniform rate of flare. The mouth of each inner section is accurately spaced from the adjoining reflecting member by a discreet amount determined by the dimensions at this point and the cutoff frequency. Since each mouth directs its sound against a curved wall, the sound is reversed or flexed back in the opposite direction between its own wall and the surrounding member. As stated, currently popular reflexed horns, with air columns up to 6-1/2 feet long have air conduits which are reversed twice within three horn sections. *Fig. 2* illustrates a horn which is reflexed three times within four horn sections.

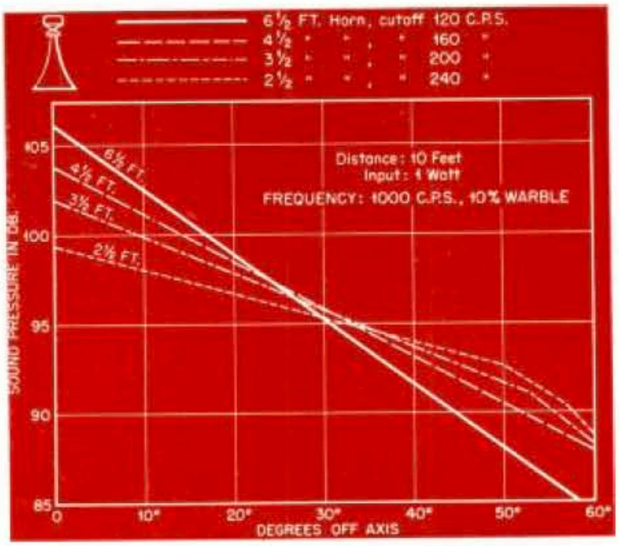
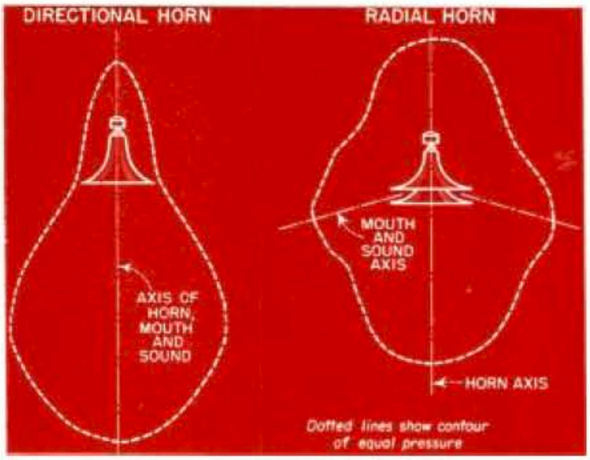


Fig. 5. Relationship of dispersion angle to frequency.

In order to obtain a horn capable of dealing with frequencies down to 30 cycles, the area of the horn would have to double every two feet of length. Assuming we start with a throat diameter of 1 inch, this horn would have an air column about 30 feet long, and the bell mouth would be approximately 12 feet in diameter! While no such horn is contemplated by any manufacturer, it could be possible to produce it in reflexed form with an over-all length of about 6 feet.

In large size reflexed horns there is a tendency for cancellation of the extreme high frequencies because of flare differences around the bends. Where these bends have a large radius, as is the case in the final bend of a large horn, phase displacement occurs because of the difference in linear distances between opposite walls of a bend. When this distance approaches ¼ wavelength or more, acoustic cancellation sets in. Reflexed horns today are capable of reproduction to about 8,000 cycles, and as this represents the limit of the average driver unit, a folded horn may be regarded as equal to a straight horn, and has the advantages of compactness and improved protection from the weather. Reflexed horns have been designed capable of transmission to over 15 kc. Except for precise research and upper high frequency studies, the reflex horn fills all requirements for speech and music reproduction down to its specific low frequency cutoff. The long, straight horn has entirely disappeared from the market.

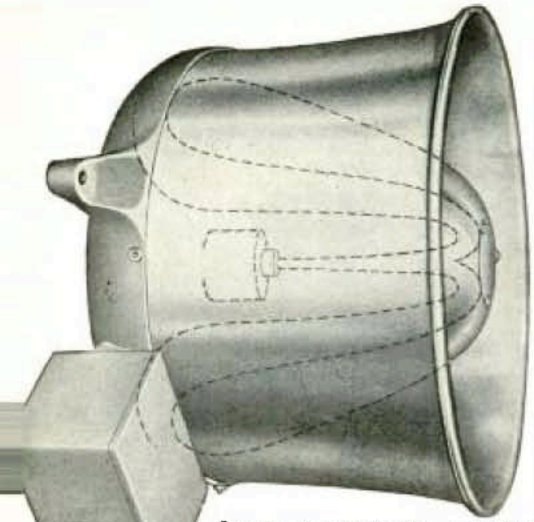


Dotted lines show contour of equal pressure

Fig. 4. Sound patterns of directional and radial loudspeakers.

The Radial Reflexed Horn

"Radial" loudspeakers refer to sound projectors which supposedly have a 360 degree horizontal distribution pattern. Speakers of this type are suspended from the ceiling and are sometimes referred to as "chandelier" speakers. As available commercially today, they are simply directional horns with a "deflector" mounted in the mouth to deflect the sound *radially* away from the mouth. Thus, when hung vertically, the sound is distributed horizontally through 360 degrees. Actually, in the case of such a radial, the mouth is now formed by the rim of the bell and the rim of the deflector, thus the sound axis is no longer the horn axis. The sound axis of a radial speaker lies on a plane with the mouth axis. Because the spacing between rim of the bell and the rim of the deflector (forming the mouth) is usually under six inches and hence only a fraction of the wavelengths of the low and middle frequencies, serious bending of the wave front in a vertical plane takes place. The resulting radiation has the shape of a toroid or doughnut, expanding outward in all directions. This diffraction phenomenon completely upsets the belief that the area immediately underneath a radial is a "dead" area. The area above and below is very much alive, and is more often than not, the location of maximum sound intensity. Along the vertical center axis, at right angles to the mouth axis, there is a focal "line" of diffracted waves, and since this position can be the only one at which all waves arrive in phase, it receives the summation of all energy originating circumferentially at the mouth. If feedback in a public address system is to be held to a minimum,



Racon marine loudspeaker, a double re-entrant type designed for operation under extremely rigorous conditions.

the microphone must *not* be placed directly underneath a radial speaker. This precaution is stated here because the writer has seen claims that such a location is a dead area.

In a straight, or reflexed directional horn, the sound axis is the same as the horn axis. The sound intensity is greatest along the horn axis, becoming weaker away from the center axis. Nevertheless, a certain amount of diffraction occurs even in the case of a supposedly directional horn and such diffraction reaches a summation at the *rear* of the horn along the center axis. Here, however, it is considerably weaker than energy in front of the horn, but the point which it is desired to make is that the diffracted waves, weak though they be, arrive in phase on the rear center axis. There is accordingly greater sound pressure here than is attained at a point at right angles to the axis for the same distance from the mouth. This is shown in *Fig. 4*.

Fig. 6. Speech type horn loudspeaker designed for railroads, mines and hazardous locations. It has a throat diameter of 2½ inches, an air column length of only 8 inches, is characterized by wide dispersion angle.

Conventional radial loudspeakers afford radiation in a three-dimensional area. As such they can be regarded as omnidirectional radiators. When the dimensions are small they are the closest approach to a point source of sound. However, for practical applications this class of projector may result in the distribution of sound into directions which represent a waste of power. For example, there is as much sound directed at the ceiling as at the floor. Also, the sound pressure output of a radial is about 10 db lower than a directional horn for the same input power and distance. The answer to a true pancake-shaped pattern is a radial with a mouth opening of at least two feet, and a bell and deflector diameter of 6 feet or more. Tied to this severe size of mouth area is the concomitant slow rate of flare. The merit in current models of radial horns lie in their practicality in affording wide coverage with minimum loudspeakers, ease of installation and wiring. They generally permit a more economical installation. Radial projectors are also effective in reducing echo in highly reverberent locations.

New model of Atlas 15-inch air column of re-entrant type speaker complete with driver unit, especially fitted for paging and talkback circuits.

Some control of the radiation pattern of a radial may be had by the direction of the mouth. Where the sound (mouth) axis forms a downward plane, the lower area will receive somewhat more energy than the area above the speaker. However, there is a definite limit to this because as the mouth axis becomes more and more divergent towards the floor, it assumes the characteristics of a conventional horn which is hung downward.

The Cobra Horn

This is a popular term given to a horn whose mouth is oblong-shaped. Its design is intended to provide wide angle distribution in a preferred plane, usually horizontal. However, while the sound beam may be widened in the plane of the wider mouth axis, there is nevertheless a strong component along the narrow axis. Here again the explanation, as in the case of radials, is due to diffraction or bending of the sound wave because of the narrow width of the horn mouth. In several current models this width, that is, the narrower one, is 2 to 4 inches, and since this (in the case of the 4″ width) corresponds approximately to one-third of the wavelength of a 1,000 c.p.s. tone, all frequencies below this are diffused in the plane of the narrow axis. In the case of a cobra horn whose mouth is only 2″ wide, this diffraction would be effective from 2,000 c.p.s. down to the horn cutoff frequency.

Fig. 7. Driver unit type loudspeaker by University designed for coupling to a horn.

Such a horn may be compact and actually have a wide angle, but it operates with poor efficiency, since a large part of its energy has been dissipated vertically. Thus in order to achieve a required sound intensity over a given angle, more amplifier power must be used than required by two conventional round-mouth speakers, angularly displaced, to cover the same area.

Directivity of Horns

The dispersion angle of a given horn will depend upon the emitted frequency. The higher the frequency the narrower the dispersion angle. Conversely, for a given frequency, the dispersion will be sharper as the horn length is increased or cutoff frequency is lowered. The larger horn will produce greater sound pressure on its axis than a short horn, but this pressure will fall off angularly at a faster rate than in the case of the short horn. This is true for frequencies well removed from cutoff. See *Fig. 5*.

For frequencies considerably above cutoff (of the shorter horn) a short horn will have uniform *total* radiated efficiency with a long horn. Thus if the output for both a short and a large horn are averaged over an extreme angle, the results will be almost identical. *Figure 5* shows the experimental results obtained with four horns of different lengths terminating in mouth diameters corresponding to one-quarter of their respective cutoff wavelengths. Along the center axis of the horn, the efficiency is proportional to horn length, demonstrating that the longer the horn the more the "channeling" effect. However, as we depart angularly from the center axis, the rate at which the pressure drops is greatest for the longest horn.

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It will also be observed that at some off-axis position, the output of a long horn becomes identical with a short horn for a specified frequency. In the case of the horns tested this is roughly 30 degrees from the center axis. Beyond this angle the shorter horn tends to exceed the longer horn in output. In the actual test the total integrated energy of each horn over an included angle of 120 degrees was found to be identical within 1 db when tested at 1000 cycles warbled tone.

From the foregoing, it is clear that to achieve a desired angular coverage in a sound installation where both music and speech reproduction is required, more horns of lower cutoff must be employed than would be necessary where only speech reproduction is required. Speech type reproducers possessing short air column lengths are therefore characterized by wide angles of dispersion. *Figure 6* shows such a loudspeaker with an air column of only 8 inches and having a useful spread of 150 degrees.

Fig. 8. Radial type loudspeaker giving 360 degree distribution of sound.