A NEW HIGH EFFICIENCY THEATRE LOUDSPEAKER OF THE DIRECTIONAL BAFFLE TYPE

By Harry F. Olson
Research Division, Engineering Dept. RCA Photophone, Inc.

Introduction

The transformation of electrical into acoustical energy may be accomplished in a multitude of ways. At the present time while practically all loudspeakers may be classed as of the diaphragm type, the essential distinguishing characteristic lies in the method of coupling between the diaphragm and the medium into which sound is to be radiated and in the method of driving the diaphragm. In general, loss of coupling between the diaphragm and the medium occurs at the lower frequencies. Among the common methods employed to increase low frequency radiation from diaphragms are, namely, the use of large diaphragms, groups of diaphragms and various shapes of baffles and horns.

General Considerations

A brief discussion of the function of the essential parts of a directional baffle[1] type of loudspeaker will now be made. A diaphragm vibrating with constant velocity coupled to an infinite tube generates the same

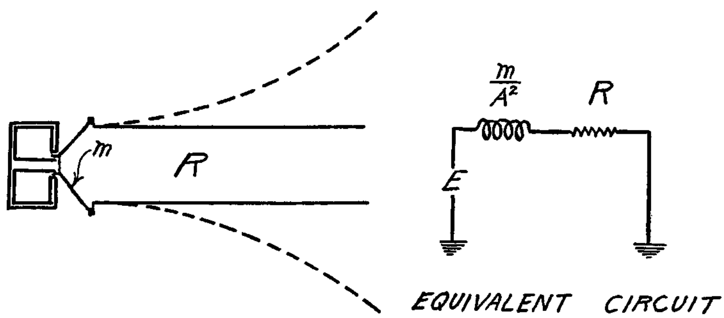


Fig. 1.

acoustic power for all frequencies. Assume that the diaphragm is a dynamic cone of mass m coupled to a tube of acoustic impedance R, Fig. 1. If the mass m of the cone is chosen so that the acoustic reactance of the cone is negligible compared to R for the range in which we are interested we will obtain a system that dissipates the same power in the acoustic resistance for any frequency within the range.

[1] The term "directional baffle" loudspeaker has been used to designate a large throat horn coupled to a cone driving unit.

For the infinite tube of constant cross section we will substitute an infinite tube of exponentially increasing cross section. It has been shown by Webster[2] that the acoustic resistance at the small end of this tube will be a constant for all frequencies above the cut-off frequency. The cut-off frequency[3] is determined by the rate of flare and may be located below the lowest frequency to be produced. If we now cut this tube at some point along the length and terminate the open end in air, the action will be altered depending upon the cross section of the resulting mouth. If this cross section is sufficiently large very slight reflection will occur at the transition from the mouth to the medium (air), and the impedance presented to the cone by the tube will be practically constant above the cut-off frequency. The system as before will dissipate the same power into the tube for the frequency range we have chosen; and consequently, neglecting slight reflection at the mouth, will dissipate constant power into the medium for this range. This system consisting of a finite flaring tube of exponentially increasing cross section coupled to a dynamic cone essentially constitutes the directional baffle type of loudspeaker.

In the d'Alembertian[4] wave equation for the axial motion in an exponential horn it is assumed that the phase is the same over a plane normal to the axis of the horn. This condition is practically satisfied provided the cross section is not greater than a wave length. It has been found experimentally that, for any particular frequency within the transmission band, additional length of horn beyond a certain point (the radius of ultimate impedance) does not affect the performance of the horn. That is, the working portion of the horn decreases with increase of frequency. Therefore, in a horn in which the axis is a straight line, the condition of the same phase over a plane normal to the axis is automatically satisfied.

To maintain the same phase over a plane normal to the axis in a folded or curled-up horn is exceedingly difficult. The condition is practically satisfied provided the diameter at any bend is less than the wavelength of the highest frequency reproduced. This places a limitation upon the amount of folding or curling that may be accomplished without impairing the horn action. If these conditions are not satisfied, destructive interference will result, and in addition certain portions of the horn will

[2] Webster, Journal of the National Academy of Sciences, 1919, pp. 275–282.

[3] C. R. Hanna and J. Slepian, A.I.E.E., 1924.

[4] Webster, *loc. cit.*

act as a reflector for the higher frequencies. These conditions ultimately result in a non-uniform response characteristic.

To obviate any possibility of a non-uniform frequency characteristic due to folding, we have employed exclusively a horn with a straight line axis. By the use of a large throat horn this objective may be accomplished without resorting to excessive length.

The low frequency cut-off of a finite exponential horn is determined by the rate of flare and the mouth opening. When the cut-off frequency has been set the mouth opening and rate of flare are fixed. There is now one remaining factor that determines the length of the horn, namely, the throat area.

At this point we will digress to point out the limitations imposed upon the size of the theater loudspeaker. In motion picture theaters in many instances the space behind the screen is limited; and in theaters having a stage presentation in addition to the motion picture, portability is a great factor. In view of the fact that the space occupied by the loudspeaker is an important factor it is essential that the loudspeaker be as short as possible. To accomplish this objective it is necessary that the throat be made as large as possible. The question then arises as to the proper driving unit that will properly match the acoustic impedance at the small end of a large throat horn. In the analysis which follows it will be shown theoretically and substantiated experimentally that a cone type of unit can be designed for a large throat exponential type of horn to yield high efficiency and good fidelity of reproduction over a wide frequency range. The type of loudspeaker[5] now being supplied with RCA Photophone equipments has been designed in accordance with the principles discussed in this analysis.

Theoretical Considerations

The loudspeaker discussed in the following theory comprises a number of essential elements each of which has certain acoustical constants. These are indicated in Fig. 2 and are as follows:

(1) A large throat horn, Z_1.
(2) A paper cone and voice coil, M_c.
(3) A box, C_B, having a felt back, R.
(4) An air chamber between the cone and horn, C_1.

1. *The Horn:*

The horn used in this loudspeaker is of the exponential type. The

[5] Photophone Loudspeaker P. L. 30.

equation expressing the area at any distance X along the axis is given by

$$S = S_0\, e^{mx}$$

where S_0 = throat area

S = area at a distance X along the axis

m = flaring constant.

The impedance characteristic and the directional characteristics of a horn are of paramount importance in predicting the usefulness of the horn. The theoretical prediction of the directional characteristics will be relegated to another paper. The impedance characteristic of this horn will now be derived.

By a suitable modification the d'Alembertian wave equation[6] for the axial motion in an exponential horn is

$$\frac{\partial^2\phi}{\partial x^2} + m\frac{\partial\phi}{\partial x} + K^2\phi = 0. \tag{1}$$

The solution of equation may be written in the form

$$\phi = \epsilon^{ax}[A \cos bx + B \sin bx]\epsilon^{i\omega t} \tag{2}$$

where $a = -m/2$,

$b = \frac{1}{2}\sqrt{4K^2 - m^2}$,

$K = 2\pi/\lambda$, λ = wavelength,

$\omega = 2\pi f$, f = frequency.

The pressure at any point in the horn is given by

$$p = \rho\dot{\phi} = i\omega\rho e^{ax}[A \cos bx + B \sin bx]e^{i\omega t}. \tag{3}$$

The volume velocity[7,8] at any point in the horn is given by

$$V = -S\frac{\partial\phi}{\partial x} = -S[ae^{ax}(A \cos bx + A \sin bx) + be^{ax}(-A \sin bx + B \cos bx)]e^{i\omega t} \tag{4}$$

where ρ = density of air.

We have now derived the expression for the pressure and volume

[6] Webster, *loc. cit.*

[7] In the acoustic analysis of this sytem pressure and volume velocity will be employed. In dealing with the mechanical system, force and linear velocity will be used. In the first system the total impedance is Z (per sq. cm.) divided by S whereas in the latter system it is $Z\,S$.

[8] Stewart and Lindsey, "Acoustics," 22 and 23.

velocity for any point in the horn. We now desire the pressure and volume velocity at the throat in terms of the pressure and volume velocity at the mouth.

The impedance at the throat is given by $Z_1 = p_1/V_1$. At the mouth the impedance is given by $Z_2 = p_2/V_2$.

We now have four equations containing A, B, p_1, V_1, p_2, and V_2 from which we may eliminate A and B and obtain the ratio of p_1 to V_1, the impedance Z_1 at the throat of the horn. This impedance in terms of Z_2 is given by the expression

$$Z_1 = \frac{\rho c}{S_1}\left(\frac{Z_2 \cos(bl - \phi) + i \sin(bl)}{iZ_2 \sin(bl) + \dfrac{\rho c}{S_2}\cos(bl + \phi)}\right) \tag{5}$$

where l = length of the horn

$\phi = \tan^{-1} a/b$

S_1 = throat area

S_2 = mouth area.

It has been shown by Crandall[9] that the resistive component of the impedance at the mouth of the horn may be expressed by[10]

$$R_2 = \frac{\rho c}{\pi R^2}\left(1 - \frac{J_1(2KR)}{KR}\right), \quad S_2 = \pi R^2 \tag{6}$$

The reactive component may be expressed by

$$X_2 = \frac{\rho c}{\pi R^2}\left(\frac{K_1(2KR)}{2K^2R^2}\right) \quad S_2 = \pi R^2. \tag{7}$$

The impedance Z_2 for the mouth of the horn is

$$Z_2 = R_2 + iX_2. \tag{8}$$

We are now prepared to calculate the impedance at the small end of the horn by substituting the values of Z_2 above in equation (5).

2. *The Cone Unit:*

The unit of this system consists of a paper cone fitted with an aluminum wire voice coil. An air chamber couples the area of the cone to the

[9] Crandall, "Theory of Vibrating Systems and Sound," p. 170.

[10] These expressions are the same as those of a piston in an infinite plane. Strictly speaking this is not a rigorous representation of the impedance at the mouth of the horn. However for practical purposes in this problem these expressions are sufficient to indicate the action.

throat of the horn. (See Fig. 2). The back of the cone is enclosed by a box with a felt back. The various components of this system will now be discussed.

The inertance[11] of the cone and voice coil is given by

$$M_c = \frac{m}{A^2} \tag{9}$$

where m = the mass of the cone and voice coil

A = the area of the cone.

We have assumed that all parts of the cone move in phase. Obviously at the higher frequencies this is not the case. However due to the heavy load imposed upon the cone and the use of a corrugated cone this condition is practically satisfied to 2500 cycles. The acoustic reactance of the cone and voice coil is

$$X_c = \frac{\omega m}{A^2} \cdot \tag{10}$$

3. *Cone Box:*

The impedance presented behind the cone must now be considered. Crandall[12] has derived an expression for the impedance presented to a piston in an infinite plane. Experiments[13] conducted upon cones in flat baffles indicate that the size of cone employed in this unit behaves as a piston to approximately 3000 cycles. The further stipulation that the side of the box containing the cone shall be an infinite plane is fulfilled for the range in which the impedance referred to is of appreciable magnitude.

With the above justifications we are prepared to express the impedance presented to the back of the cone. This consists of two parts: the resistive and reactive components. The resistive component is given by

$$R_B = \frac{\rho c}{\pi R'^2}\left(1 - \frac{J_1(2KR')}{KR'}\right), \quad R' = \text{Radius of cone.} \tag{11}$$

The reactive component is given by

$$X_B = \frac{\rho c}{\pi R'^2}\left(\frac{K_1(2KR')}{2K^2R'^2}\right). \tag{12}$$

[11] Stewart and Lindsey, "Acoustics," 23.

[12] Crandall, *loc. cit.*

[13] Wolff and Malter, Journal Acoustical Society, vol. II, 1930.

The air chamber behind the cone is enclosed by a box which has a felt back. The purpose of the felt is to absorb any sound striking it and thus prevent standing wave systems which would cause abrupt changes with frequency in the impedance presented behind the cone. At the higher frequencies the absorption of the felt is practically unity and the sound wave flows from the cone into the felt. At low frequencies however the

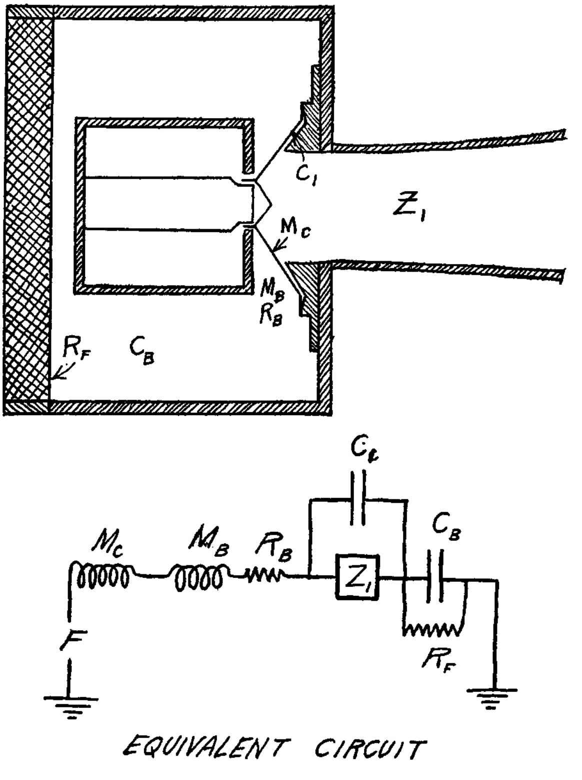


FIG. 2.

absorption is very small and as a consequence a capacitive reactance is presented to the cone. We will assume the most unfavorable condition, in which the absorption is zero. The capacitance of the box is then given by

$$C_B = \frac{V}{\rho c^2} \tag{13}$$

where V = volume of the box
c = velocity of sound
ρ = density of air.

The acoustic capacitive reactance presented to the cone in series with the horn load is

$$X_{BC} = -\frac{1}{\omega C_B} = -\frac{\rho c^2}{\omega V}. \tag{14}$$

This equation holds until the dimensions of the box are comparable to a quarter wavelength. Above this frequency the absorption due to the felt is practically unity and also the impedance due to the box may be neglected.

4. *The Air Chamber:*

The purpose of the air chamber is to act as a transformer between the area of the cone and the smaller area of the throat of the horn. In accomplishing this a capacitance results which is indicated by C_1 in Fig. 2.

The capacitance of the air chamber is given by

$$C_1 = \frac{V}{\rho c^2}. \tag{15}$$

The acoustic capacitive reactance of the air chamber is

$$X_{1C} = -\frac{\rho c^2}{\omega V}. \tag{16}$$

We have now obtained expressions for all the important impedances in the acoustic system.

Equivalent Electrical Circuit of the Loud Speaker and Efficiency:

The equivalent electrical circuit of the entire acoustic system is shown in Fig. 2. The acoustic impedance at the point F will be indicated by the expression

$$Z_T = R_T + iX_T. \tag{17}$$

The mechanical impedance of the acoustic system at the point F is

$$z = r + ix = A^2(R_T + iX_T) \tag{18}$$

where A = the area of the cone.

In the case of moving coil loudspeaker the motional impedance[14] is given by the expression

[14] Kennelly and Pierce, Proc. A.A.A.S., vol. 48, 1912.

$$Z_m = R_M + iX_m = \left(\frac{r - ix}{r^2 + x^2}\right)(Bl)^2 \tag{19}$$

where B = flux density

and l = length of wire in the voice coil.

The principal object in obtaining the motional impedance is to predict the efficiency[15,16] which in turn indicates the performance of the loudspeaker. The efficiency is given by the expression

$$Eff. = \frac{R_m}{R_m + R_d} \tag{20}$$

where R_m = motional resistance

R_d = damped resistance of the voice coil.

Results

In the preceding section we have derived expressions for all the important impedances in the acoustic system. The problem in this type of loudspeaker is to apportion these various impedances so that a uniform output of acoustic energy over a wide frequency band will be obtained.

The response and dynamic characteristics of a six-inch cone[17] were found best adapted to this type of loudspeaker. As will be seen from the equivalent circuit Fig. 2, to maintain a uniform dissipation in Z_1 it is important that the mass of the cone be small. This was accomplished by employing an aluminum wire voice coil and an extremely light rigid paper cone. The non-uniform frequency response at the higher frequencies commonly encountered when light paper of high stiffness is employed was obviated by suitable corrugation of the cone.

The size of throat that will present a tolerable acoustic impedance to the cone, and at the same time not impair the high frequency response due to absorption along the walls or cause destructive interference in the air chamber, is 4″×4″. The mouth of the baffle (43″×58″) was chosen so that good radiation characteristics will be obtained at low frequencies. This is evidenced by the curve R_2, Fig. 3, the acoustic resistance of the mouth of the loudspeaker. It was decided to limit the length of the baffle to 50 in. which places the cut-off due to flare in the neighborhood of 100 cycles. The impedance characteristic (R_1, X_1) at the throat is

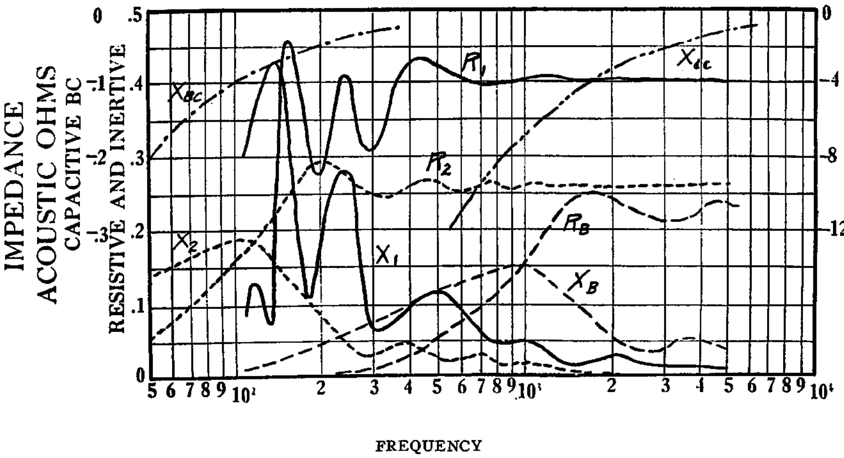
[15] E. C. Wente and A. L. Thuras, Bell System Technical Journal, January, 1928.

[16] C. R. Hanna, A.I.E.E., 1928.

[17] C. W. Rice and E. W. Kellogg, A.I.E.E., 1925.

shown in Fig. 3. Due to the finite length of the baffle the acoustic resistance falls off in a series of decreasing maxima. This reduction in resistance is compensated for by the reduction in reactance in other parts of the system and as a consequence the dissipation in R_1 is not materially decreased at the lower frequencies. The primary objective is to maintain the dissipation in this resistance as uniform with frequency as possible.

The capacitive reactance X_{BC} due to the cone box is shown in Fig. 3. The size of this box was chosen so that the reduction in current in the equivalent circuit in Fig. 2 is not appreciable above 100 cycles.



R_1 *Throat Resistance*
X_1 *Throat Reactance*
R_2 *Mouth Resistance*
X_2 *Mouth Reactance*
C_{IC} *Air Chamber Reactance*
C_{BC} *Cone Box Reactance*
R_B *Resistance—Back of Cone*
X_B *Reactance—Back of Cone*

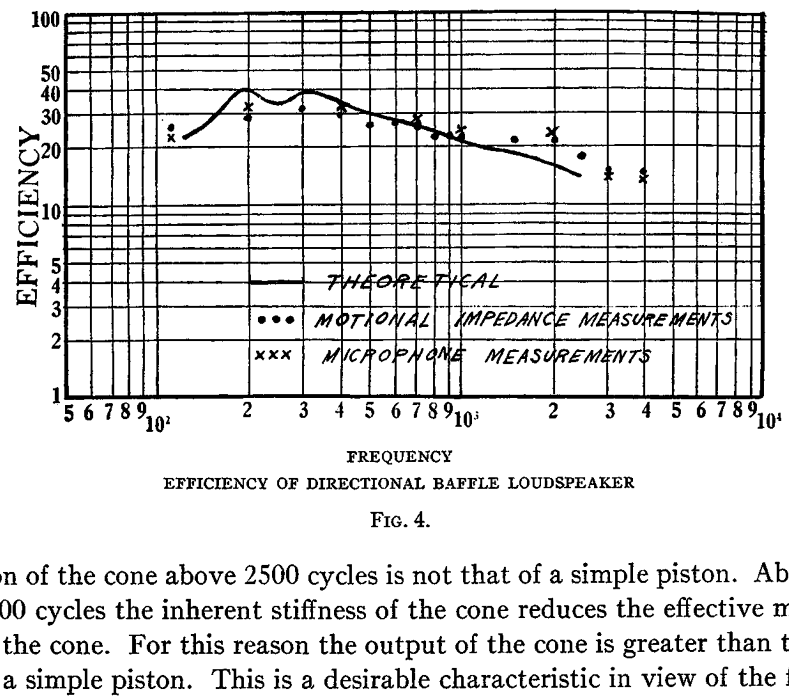
FREQUENCY IMPEDANCE CHARACTERISTICS OF THE COMPONENTS OF THE ACOUSTIC SYSTEM

Fig. 3.

The reactance X_{1C} due to the air chamber is shown in Fig. 3. The dimensions of the air chamber were chosen so that destructive interference was eliminated up to the highest frequency reproduced. The separation between the air chamber and diaphragm is 1/8 in. which allows the diaphragm to perform the large excursion necessary for full power output at the lower frequencies. The resulting capacitance resulting from this volume increases the dissipation in Z_1 due to the improved power factor.

The reactance Z_B presented to the back of the cone is shown in Fig. 3. This reactance reduces the dissipation in the impedance Z_1 but this reduction is not extremely large when cognizance is taken of the mass reactance of the cone.

The theoretical efficiency as determined by equation (20) is shown by the curve in Fig. 4. The theoretical efficiency cannot be predicted by analysis as outlined here above 2500 cycles because the mode of vibra-



EFFICIENCY OF DIRECTIONAL BAFFLE LOUDSPEAKER

FIG. 4.

tion of the cone above 2500 cycles is not that of a simple piston. Above 2500 cycles the inherent stiffness of the cone reduces the effective mass of the cone. For this reason the output of the cone is greater than that of a simple piston. This is a desirable characteristic in view of the fact that the acoustic output is increased.

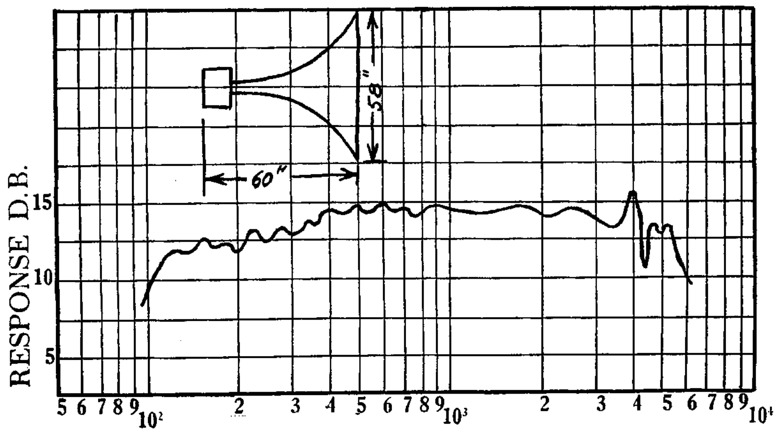
The motional resistance was determined experimentally and the efficiency computed from equation (20). The results are shown in Fig. 4.

The efficiency of the reproducer was also determined by measuring the total acoustic output by means of a calibrated condenser microphone and comparing this to the electrical input. Pressure measurements were made on the surface of a sphere with the loudspeaker at the center. The surface of the sphere was divided into elements and the energy traversing each element determined. The summation of the increments of energy gives the total energy emitted by the loudspeaker. The measuring microphone was calibrated by means of a Rayleigh disc. The energy emitted by the back of the cone is also included.

It will be seen from Fig. 4 that the results from the three methods are in close agreement.

As shown by the results in Fig. 4 high efficiency is obtained with this type of reproducer. Certain modifications were made in the manufactured reproducers to facilitate construction in a large quantity which results in a slight reduction in efficiency from that indicated here.

The decrease of efficiency with frequency Fig. 4 is not serious when cognizance is taken of the fact that efficiency is proportional to the



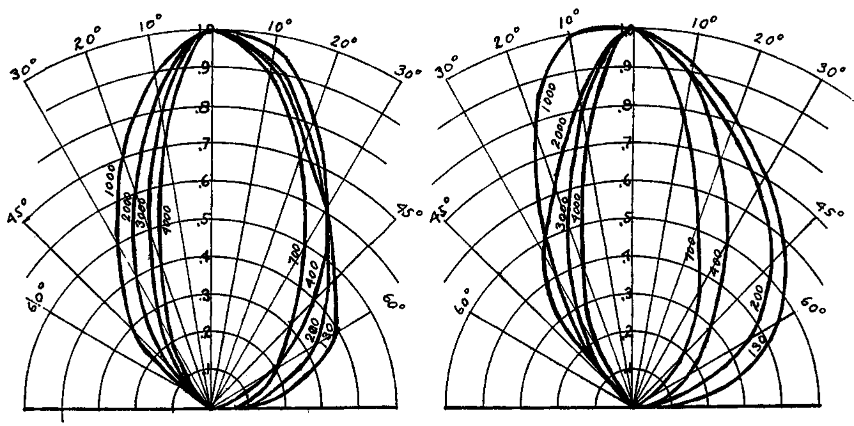
FREQUENCY
RESPONSE FREQUENCY CHARACTERISTIC
OF
LARGE DIRECTIONAL BAFFLE LOUDSPEAKER

square of the delivered pressure. For this reason efficiency expressed in per cent is an extremely sensitive measure of the performance of a loudspeaker. Expressed in terms that are more descriptive from the standpoint of sound reproduction the maximum variation is approximately three decibels. As will be seen from the response and directional characteristics the slight difference in the directional characteristics between high and low frequencies together with the above efficiency characteristic leads to a fairly uniform response characteristic.

RESPONSE MEASUREMENTS

At the present time response and directional characteristics are the best criterion of the performance of a loudspeaker. The response characteristic[18] of this loudspeaker was taken on the axis at a distance of 20 ft. from the mouth in an unobstructed medium (air).[19] It is perhaps needless to say that response curves made on loudspeakers in rooms have an extremely limited significance unless a large number of curves are taken and the data carefully analyzed to determine the influence of the room.

The response characteristics (Fig. 6) and associated directional characteristics (Fig. 7) indicate that the acoustic power delivered by this loudspeaker does not show any abrupt change with frequency. This is partially accomplished by presenting to the cone an acoustic impedance that does not exhibit any abrupt changes with frequency. The uneven



Long Axis *Short Axis*

DIRECTIONAL CHARACTERISTICS

FIG. 6.

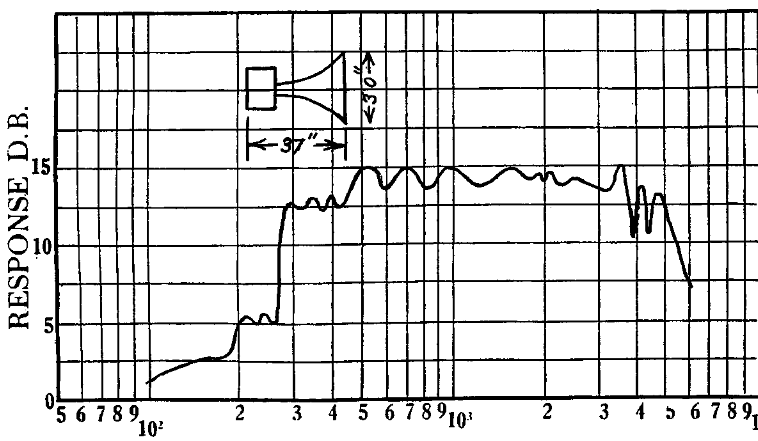
response some times encountered in cone type loudspeakers at the higher frequencies has been reduced in this loudspeaker to a negligible extent by the reduction in mass of the cone and moving coil system, by suitable processing of the paper cone and by the load imposed by the horn.

[18] The response measurements shown in this paper were made with a microphone calibrated by a Rayleigh disc. This gives the sound pressure in the undisturbed sound field. For the common condenser microphone the pressure at the microphone is twice that in the free space for the higher frequencies. In general in sound motion picture recording the practice is to ignore this and equalize the system to give uniform electrical output for constant sound pressure at the diaphragm. Under ideal conditions this will accentuate the high frequency output at the loudspeaker. The argument in favor of this procedure is that it overcomes transfer and other losses which occur at the higher frequencies.

[19] L. Malter, Journal Soc. Motion Picture Engineers, xiv (1930), 611.

This loudspeaker due to its high efficiency and rugged construction is capable of delivering large acoustic outputs (from one to two watts of sound energy) without distortion. This factor combined with the directional characteristics exhibited by this loudspeaker makes it possible to supply a large theater with sounds of good quality with a single loudspeaker.

For theaters that exhibit high reverberation characteristics and other acoustic difficulties it is necessary to attenuate the low frequency response of the loudspeaker to obtain the most satisfactory results. For



FREQUENCY.
RESPONSE FREQUENCY CHARACTERISTIC
OF
SMALL DIRECTIONAL BAFFLE LOUDSPEAKER

FIG. 7.

this purpose another loudspeaker employing the same unit as described above but with a baffle having a higher low frequency cut-off is used. The response characteristic of this loudspeaker is shown in Fig. 8. The efficiency and power capabilities of this loudspeaker is the same within its response limits as the loudspeaker described in detail above.

In conclusion the author wishes to express his appreciation to Mr. J. Weinberger under whose direction this work was done, to Mr. S. Goldman for valuable aid in computing and assembling the data and to Mr. L. Malter who was associated with the author during the early part of this investigation.

RCA Review Apr 1937

HORN LOUD SPEAKERS

By

HARRY F. OLSON

RCA Manufacturing Co., Camden, N. J.

PART I. IMPEDANCE AND DIRECTIONAL CHARACTERISTICS

INTRODUCTION

HORNS have been widely used for centuries for increasing the radiation from a sound source. The principal virtue of a horn resides in the possibility of presenting practically any value of acoustic impedance to the sound generator. This feature is extremely valuable for obtaining maximum overall efficiency in the design of an acoustic system. As an example, in a horn loud speaker high efficiency is obtained by designing the system so that the driving force works against resistance instead of inertia of the diaphragm. Employing suitable combination of horns, directional characteristics which are independent of frequency, as well as practically any type of directional pattern, may be obtained. The combination of high efficiency and the possibility of any directional pattern makes the horn loud speaker particularly suitable for large scale sound reproduction. It is the purpose of these papers to consider some of the factors which influence the performance and characteristics of horn loud speakers.

HORN THROAT IMPEDANCE CHARACTERISTICS

The horn throat acoustic impedance characteristic is of paramount importance in designing a horn loud speaker because the dissipation or radiation of energy may be considered to take place in the resistive or real part of the throat acoustic impedance. The throat impedance characteristic[1, 2, 3, 4, 5] depends upon the length, throat and mouth dimensions and the shape of the horn. It is the purpose of this section to consider the factors which determine the impedance characteristics

[1] Webster, A. G. *Jour. Nat. Acad. Sci.*, Vol. 5, P. 275, 1919.
[2] Stewart, G. W. *Phys. Rev.*, Vol. 16, P. 313, 1920.
[3] Goldsmith and Minton, *Proc. Inst. Rad. Eng.*, Vol. 12, P. 423, 1924.
[4] Slepian and Hanna, *Jour. Amer. Inst. Elect. Eng.*, Vol. 43, P. 393, 1924.
[5] Ballantine, S. *Jour. Franklin Inst.*, Vol. 203, P. 85, 1927.

of a horn a)the relation between the impedance and response characteristics.

The horns most commonly used for sound reproduction are the conical and the exponential. Consequently the following discussion will be confined to these two types.

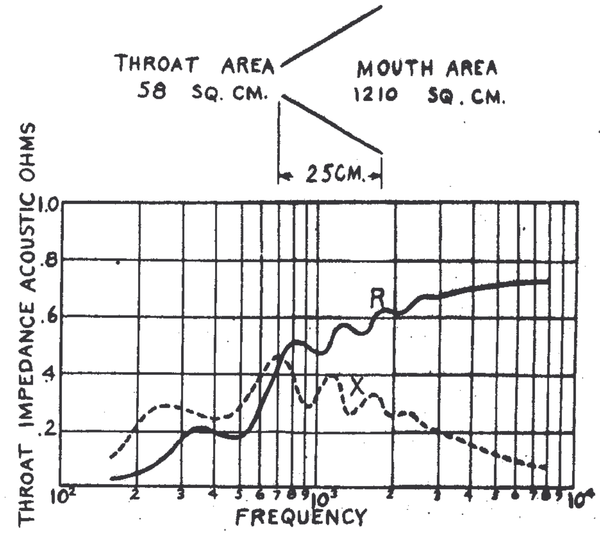


Fig. 1—Acoustic impedance characteristic, at the throat of a conical horn of the dimensions shown for comparison with the exponential horn of Fig. 2. *R*, resistive component. *X*, reactive component.

In the case of the conical horn the area at any point x along the axis is,

$$S = S_1 x^2 \qquad (1)$$

where S_1 = area at $x = 1$,
S_1 = throat area

In the case of the exponential horn the area at any point x along the axis is,

$$S = S_1 \varepsilon^{mx} \qquad (2)$$

where S_1 = area at $x = 0$,
S_1 = throat area,
and m = flaring constant.

The expression for the throat acoustic impedance of the conical horn is,

$$Z_1 = \frac{j\rho\omega}{S_1}\left[\frac{Z_2S_2khl\cos[k(l-h)] + (j\rho\omega hl - Z_2S_2h)\sin[k(l-h)]}{j\rho\omega l - Z_2S_2(1+k^2lh)\sin[k(l-h)] + j\rho\omega klh + Z_2S_2k(l-h)\cos[k(l-h)]}\right] \qquad (3)$$

where S_1 = area of the throat, square centimeters,

S_2 = area of the mouth, square centimeters,

$$k = \frac{2\pi}{\lambda}$$

λ = wavelength, centimeters,

l = distance from the apex to the mouth, centimeters,

$\omega = 2\pi f$

f = frequency, cycles per second,

h = distance from the apex to the throat, centimeters,

ρ = density of air, grams per cubic centimeter,

Z_2 = acoustic impedance of the mouth, acoustic ohms.

The expression for the throat acoustic impedance of the exponential horn is,

$$Z_1 = \frac{\rho c}{S_1}\left[\frac{S_2 Z_2 [\cos(bl-\theta)] + j\rho c[\cos(bl)]}{jS_2 Z_2 \sin(bl) + \rho c[\cos(bl+\theta)]}\right] \quad (4)$$

where S_1 = area of the throat, square centimeters,

S_2 = area of the mouth, square centimeters,

l = length of the horn, centimeters,

Z_2 = acoustic impedance of the mouth, acoustic ohms,

$$\theta = \tan^{-1}\frac{a}{b}$$

$$a = \frac{m}{2}$$

and $b = \frac{1}{2}\sqrt{4k^2 - m^2}$

Throat impedance frequency characteristics of a conical and exponential horn of the same mouth and throat area and length computed from equations 3 and 4 are shown in Figures 1 and 2.

These characteristics show that the exponential horn has a definite low-frequency cut-off above which the throat resistance increases rapidly and becomes a constant. On the other hand, the throat resistance of the conical horn increases slowly with frequency and shows no definite low-frequency cut-off. Furthermore, the impedance frequency characteristics of the exponential horn show a larger ratio of resistance to reactance. For these reasons the exponential horn is more desirable and accounts for its almost universal use in horn loud speakers. In view of its wide-spread use it is interesting to examine some of the other characteristics of exponential horns.

The throat acoustic impedance characteristic as a function of the mouth, with the flare and throat kept constant, is of interest in determining the optimum dimensions for a particular application. The impedance characteristics of four finite horns having a cut-off of 100 cycles, throat diameter of one inch and mouth diameters of 10, 20, 30, and 40 inches and the corresponding infinite horn are shown in Fig. 3. These results may be applied to horns of a different flare by multiplying all the dimensions by the ratio of 100 to the new cut-off frequency. The cut-off frequency of an exponential horn is given by,

$$2\omega = mc \quad (5)$$

where $\omega = 2\pi f$, f = frequency,
and c = velocity of sound.

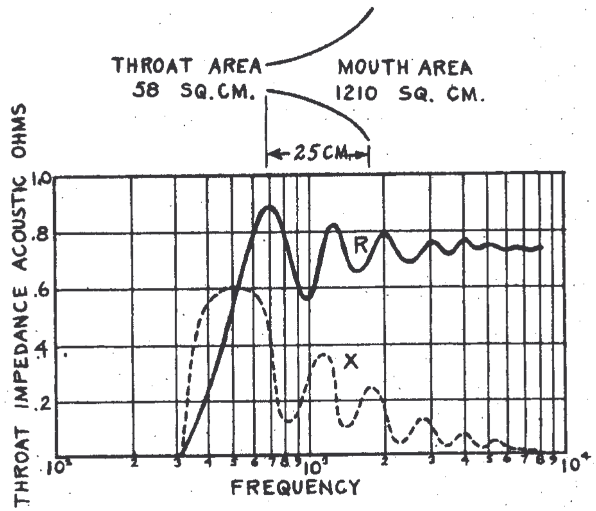


Fig. 2—Acoustic impedance characteristic, at the throat of an exponential horn of the dimensions shown and cut-off due to flare of 320 cycles, for comparison with the conical horn of Fig. 1. *R*, resistive component. *X*, reactive component.

The radiation resistance of a mouth 10 inches in diameter is relatively small below 500 cycles. The large change in impedance in passing from the mouth to the free atmosphere introduces reflections at the mouth and as a result wide variations in the impedance characteristic as shown in Figure 3A. For example, the first maximum in the resistance characteristic is 150 times the resistance of the succeeding minimum.

By doubling the diameter of the mouth the maximum variation in the resistance characteristic is 7.5, Figure 3B.

Figure 3C shows the impedance characteristic of)horn with a mouth diameter of 30 inches. The maximum variation in the resistance characteristic of this horn is 2.

The impedance characteristic of a horn with a mouth diameter of 40 inches, Figure 3D, shows a deviation in resistance of only a few per cent from that of the infinite horn of Fig. 3E.

These results show that as the change in impedance in passing from the mouth to the free atmosphere becomes smaller by employing a mouth diameter comparable to the wavelength, the reflection becomes correspondingly less and the variations in the impedance characteristic are reduced.

Due to the impracticability of a horn mouth diameter comparable to the wavelength for low-frequency loud speakers, it is interesting to note that a relatively smooth response characteristic can be obtained from a horn having an impedance characteristic varying over wide limits. For example, consider a moving-coil mechanism coupled to the throat of a horn and fed by a vacuum-tube amplifier, the sound power output is the real part of

$$\text{Power} = \left(\frac{e}{|z_T|}\right)^2 z_m \qquad (6)$$

$$\text{where } z_m = \left\{\frac{(Bl)^2}{A^2\,(R + jX) + jx}\right\} 10^{-9}$$

B = air gap flux density, gausses,
l = length of wire in the voice coil, centimeters,
A = area of the diaphragm, square centimeters
R = acoustic resistance at the throat, acoustic ohms,
X = acoustic reactance at the throat, acoustic ohms,
x = mechanical reactance of diaphragm and coil system, mechanical ohms,
$z_T = r_d + r_t + z_m$
r_d = voice coil resistance, ohms,
r_t = amplifier output resistance, ohms,
and e = amplifier open-circuit voltage, volts.

Equation 6 shows, providing suitable constants may be chosen for the driving mechanism, that the throat resistance R may vary over wide limits without introducing large variations in the power output. As a specific example, Figure 4 shows the power output as a function of the frequency for a horn, having all dimensions 2½ times that of Figure 5B and driven by a mechanism and vacuum tube having the

constants)dicated by the caption of Figure 4. **Although the impedance variation is 6 to 1, the variation in power output is only 2 *db*.**

The throat acoustic impedance characteristic as a function of the throat size with the mouth and flare held constant is of interest in

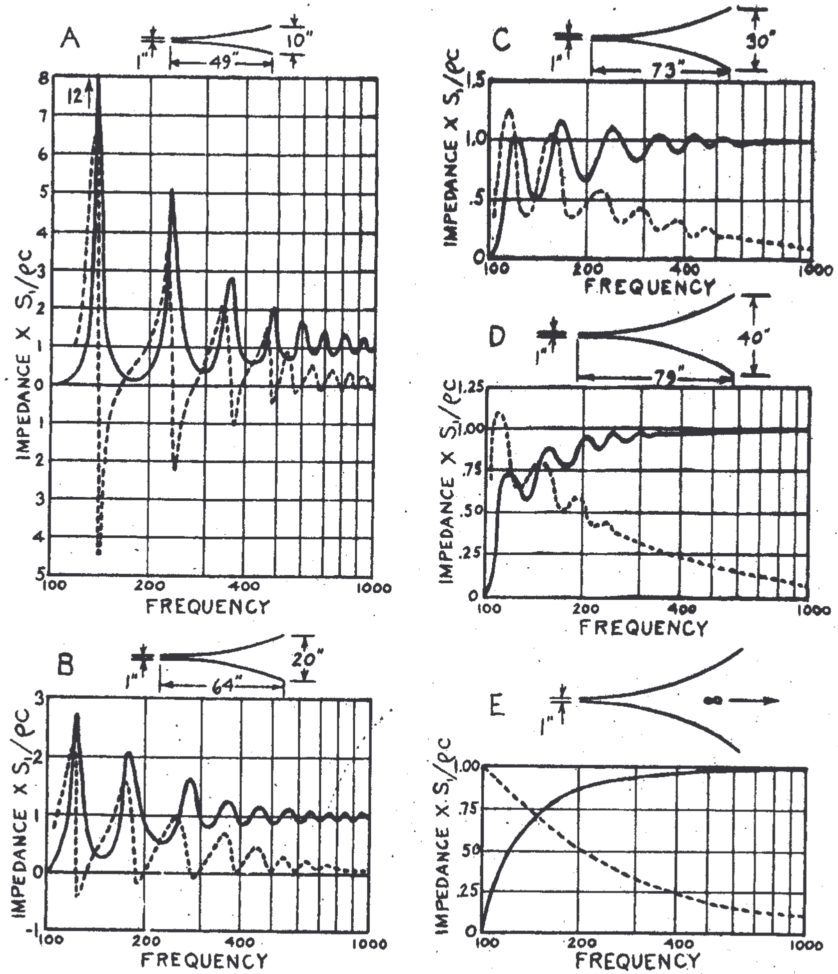


Fig. 3—The throat impedance characteristics of a group of exponential horns, with a flare cut-off of 100 cycles and a throat diameter of 1 inch, as a function of the mouth diameter, ρ density of air, grams per cubic centimeter, C velocity of sound, centimeters per second, and S_1 area of the throat, square centimeters.

determining the optimum length and a suitable matching impedance for the driving mechanism. The impedance characteristics of 4 horns having a cut-off of 100 cycles, mouth diameter of 20 inches and throat diameter of 1, 2, 4 and 8 inches are shown in Figure 5. A consideration of these characteristics shows that the throat size has no appreciable effect upon the amplitude of the variations in the impedance characteristics. However, the separation in frequency between successive maxima is increased, as the throat becomes larger, due to the decreased length of the horn. The frequency at which the first maximum in the resistance characteristic occurs becomes progressively higher as the length is decreased.

Directional Characteristics

The directional characteristic of a loud speaker is the response as a function of the angle with respect to some axis of the system.

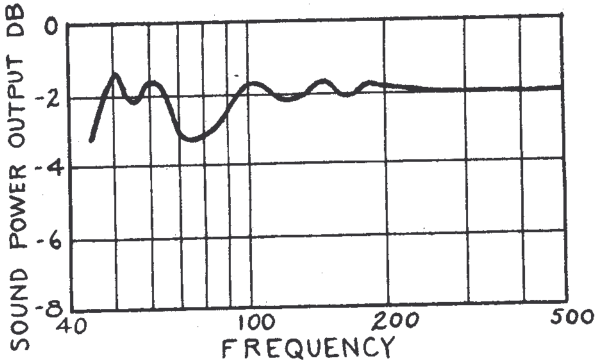


Fig. 4—Power output characteristic of a horn (horn of Fig. 5B. with all dimensions multiplied by 2½) coupled to a 10½ inch, 10 gram, diaphragm driven by a 5 gram aluminum voice coil in a field of 20000 gausses. Damped resistance of voice coil 20 ohms. Impedance of vacuum tube 35 ohms.

These may be plotted as a system of polar curves for various frequencies or as response-frequency curves for various angles with respect to the axis.

The directional characteristic of a horn depends upon the shape, mouth opening, and the frequency. It is the purpose of this section to examine and consider some of the factors which influence the directional characteristics of a horn.

The phase and particle velocity of the various incremental areas which may be considered to constitute the mouth determines the directional characteristics of the horn. The particular complexion of the velocities and phase of these areas is governed by the flare and dimensions and shape of the mouth. In these considerations the mouth will be of circular cross section and mounted in a large flat baffle. The mouth of the horn plays a major role in determining the directional characteristics in the range where the wavelength is greater than the

mouth diameter. The flare is the major factor in determining the directional characteristics in the range where the wavelength is less than the mouth diameter.

Figure 6 shows the effect of the diameter of the mouth for a constant flare, upon the directional characteristics[6] of an exponential horn. At the side of each polar diagram is the diameter of a vibrating piston

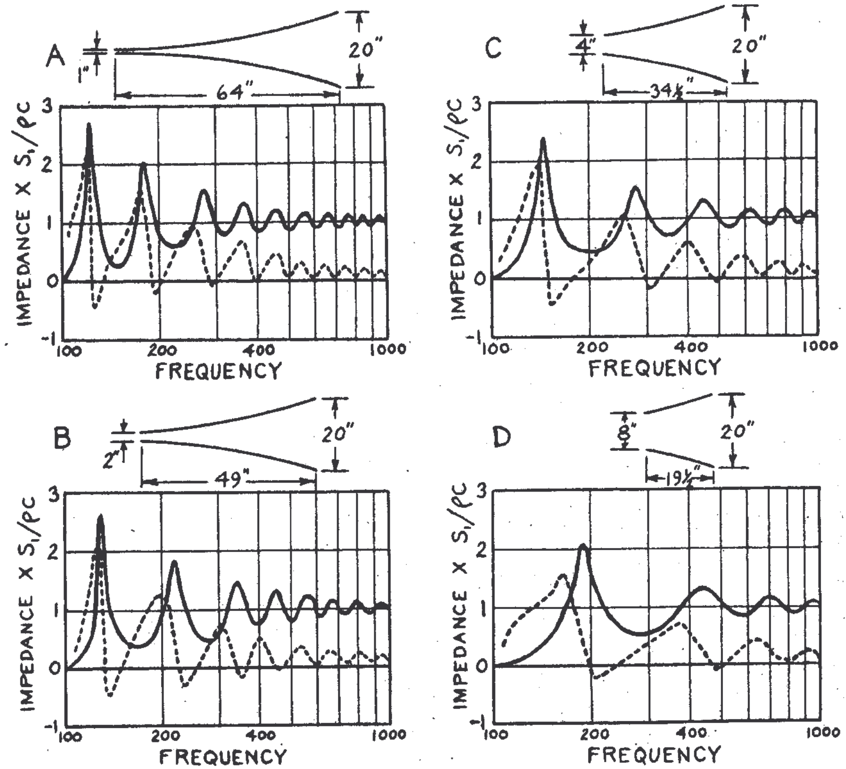


Fig. 5—The throat impedance characteristics of a group of exponential horns, with a flare cut-off of 100 cycles and a mouth diameter of 20 inches, as a function of the throat diameter. ρ density of air, grams per cubic centimeter, C velocity of sound, centimeters per second, S_1 area of the throat, square centimeters.

which will yield approximately the same directional characteristic. It will be seen that up to the frequency at which the wavelength becomes comparable to the mouth diameter, the directional characteristics are practically the same as those of a piston of the size of the mouth.

[6] Goldman, S. *Jour. Acous. Soc. Amer.*, Vol. 5, P. 181, 1934, reports the results of an investigation upon the directional characteristics of exponential horns at 15000 and 25000 cycles. A comparison can be made with the results shown in Figures 6 and 7 by increasing the dimensions of the horns used by him to conform with those shown here and decreasing the frequency by the factor of increase in dimensions. Such a comparison shows remarkable agreement between the two sets of data.

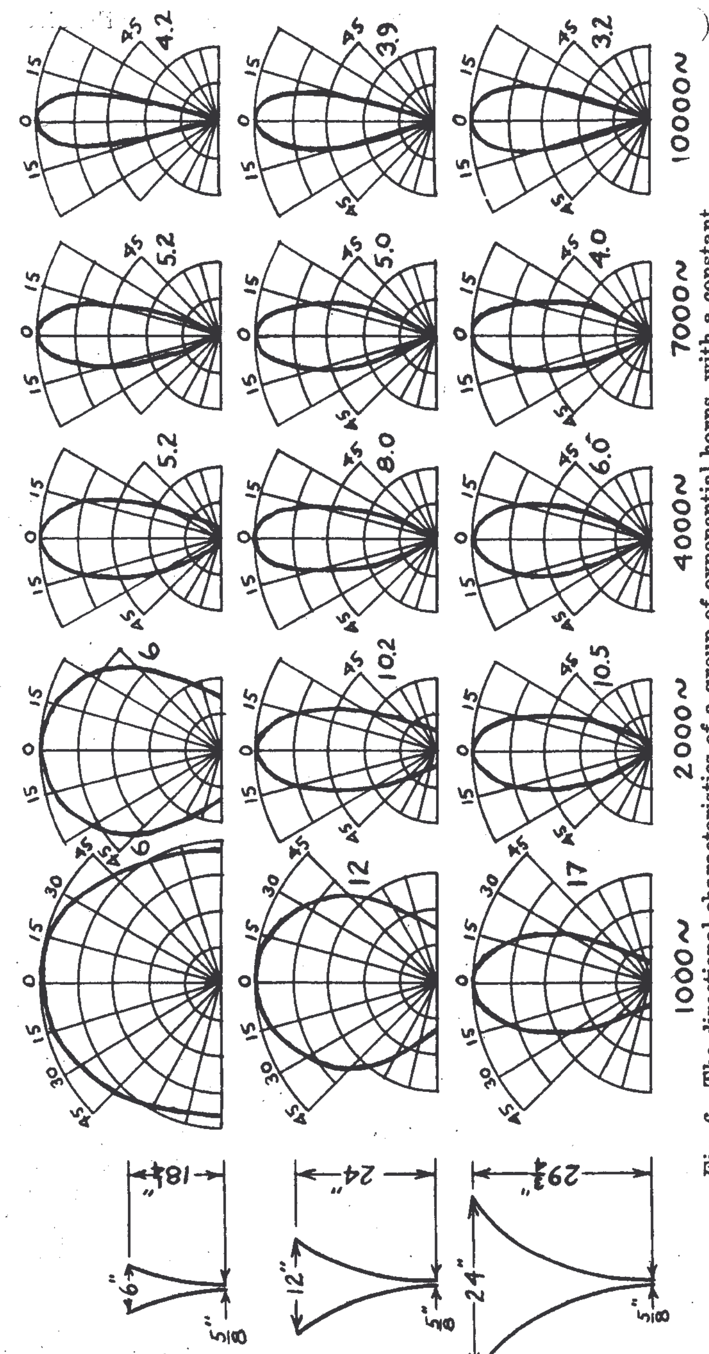


Fig. 6—The directional characteristics of a group of exponential horns, with a constant flare and throat diameter of ⅝ inch, as a function of the mouth diameter. The number at the right of each polar diagram indicates the diameter of a circular piston which will approximately yield the same directional characteristic. The length of the radius vector to a point on the curve is proportional to the sound pressure in the direction of the angular coordinate.

Above th frequency the directional characteristics are practically independent of the mouth size and appear to be governed primarily by the flare.

To further illustrate the relative effects of the mouth and flare, Figure 7 shows the effect of different rates of flare, for a constant mouth diameter, upon the directional characteristics of an exponential horn. These results also show that for the wavelengths larger than the mouth diameter the directional characteristics are approximately the same as those of a vibrating piston of the same size as the mouth. Above this frequency the directional characteristics are broader than that obtained from a piston the size of the mouth. From another point of view, the diameter of the piston which will yield the same directional characteristic is smaller than the mouth. These results also show that the directional characteristics vary very slowly with frequency at these smaller wavelengths. Referring to Figure 7 it will be seen that for any particular high frequency, 4,000, 7,000 or 10,000 cycles per second, the directional characteristics become progressively sharper as the rate of flare decreases.

The above results show that practically any directional characteristic can be obtained over a certain range of frequencies. In some cases, as for example, high-power announce over large distances, it is desirable to confine the radiation to a very small solid angle. To do this requires a very large mouth and a slow rate of expansion. Such a horn is very cumbersome and difficult to handle. A sharp directional characteristic may be obtained by employing a ring-type mouth which, in effect, increases the diameter. Providing the width of the ring shaped mouth is small, compared to the wavelength, the directional characteristics for a ring may be used to predict the performance.

The expression for the directional characteristics[7] of a circular ring is given by,

$$R = J_o\left(\frac{kd}{2}\sin\theta\right) \qquad (7)$$

where R = ratio of the sound pressure at an angle θ off the normal speaker axis to that on the axis.

$k = \frac{2\pi}{\lambda}$ $\qquad \lambda$ = wavelength,

d = diameter of the ring,

J_o = Bessel function of zero order.

[7] Stenzel, H. *Elek. Nach. Tech.*, Vol. 4, No. 6, P. 1, 1927.

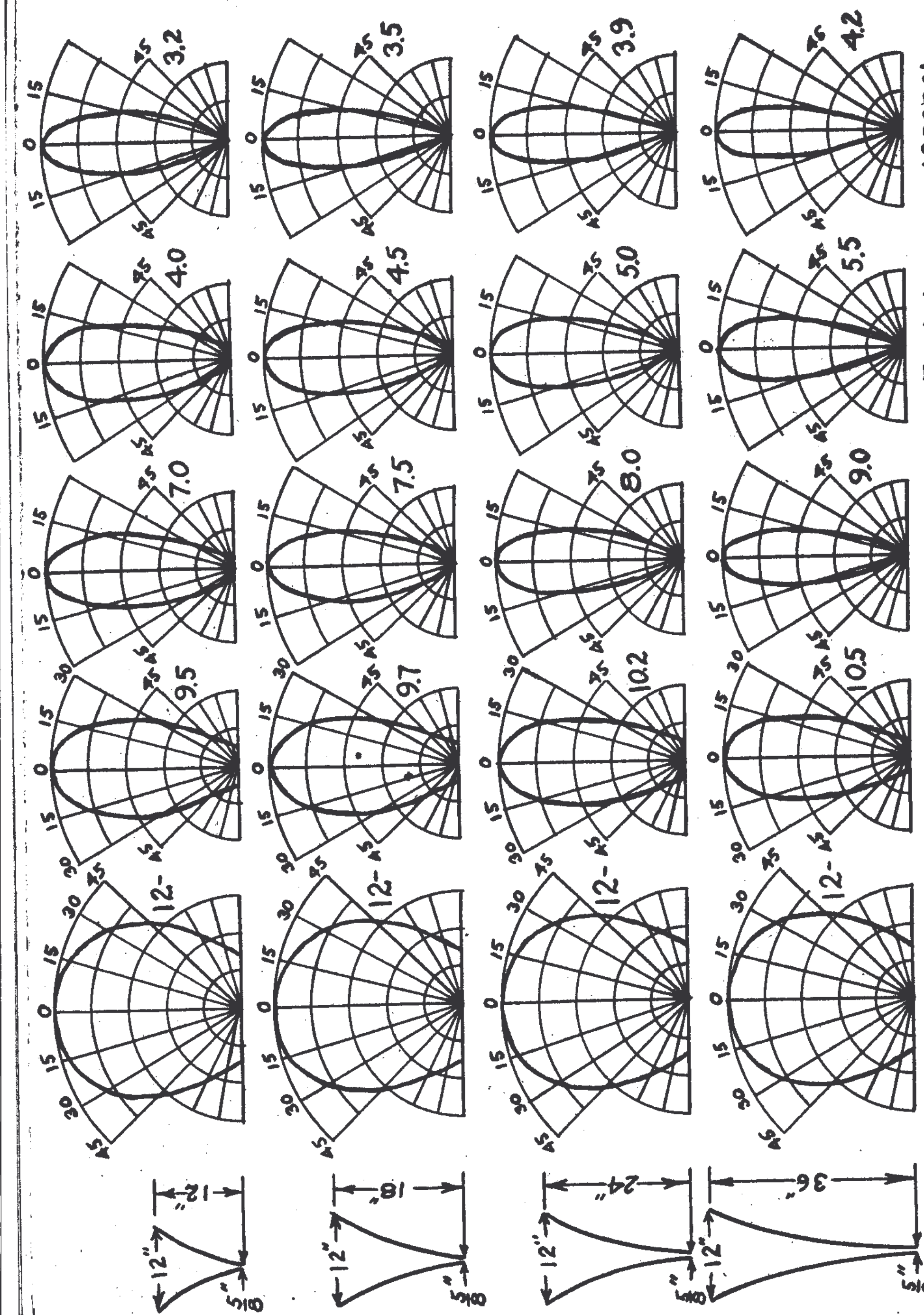


Fig. 7—The directional characteristics of a group of exponential horns, with a mouth diameter of 12 inches and a throat diameter of ⅝ inch, as a function of the flare. The number at the right of each polar diagram indicates the diameter of a circular piston which will yield approximately the same directional characteristic. The length of the radius vector to a point on the curve is proportional to the sound pressure in the direction of the angular coordinate.

This equation shows that for a particular frequency the directional characteristics are only a function of the diameter of the ring.

An example of how the directional characteristics may be sharpened by employing a ring-shaped mouth compared to the conventional mouth is depicted in Figure 8. This method is particularly adapted to loud speakers designed to cover a small frequency band, such as high-power announce, in which the response is confined to 2 or 3 octaves. When the frequency range is wide, considerable variation in the directional characteristics occurs together with additional lobes at the higher frequencies.

The exponential horns shown in Figs. 6 and 7 have directional characteristics which vary with frequency. The lower frequencies are projected through a relatively large angle, and as the frequency increases, the sound distribution angle decreases and becomes quite small for wavelengths small compared with the diameter of the mouth. This kind of directional pattern introduces frequency discrimination for points removed from the axis and is not suitable for high fidelity reproduction of sound. A sphere vibrating radially radiates sound uniformly outward in all directions. A portion of a spherical surface, large compared to the wavelength and vibrating radially, emits uniform sound radiation over a solid angle subtended by the surface at the center of curvature. Therefore, to obtain uniform sound distribution over a certain solid angle, the radial air motion must have the same phase and amplitude over the spherical surface intercepted by the angle having its center of curvature at the vertex and the dimensions of the surface large compared with the wavelength. When these conditions are satisfied for all frequencies, the response characteristic will be independent of the position within the solid angle.

A loud speaker[8, 9, 10, 11, 12] consisting of a large number of small horns with the axis passing through a common point will satisfy, for all practical purposes, the requirements of uniform phase and amplitude over the spherical surface formed by the mouths of the horns. A cellular or multi-horn of this type is shown in Figure 9. This particular horn system consists of 15 horns arranged in 5 vertical rows and 3 horizontal rows. The mouth opening of each individual horn is 8" x 8". The horizontal and vertical angle between the axis of the individual horns is approximately 17°.

[8] Slepian, J., U. S. Patent 1684975.
[9] Hanna, C. R., U. S. Patent 1715703.
[10] Wente, E. C., U. S. Patent 1992268.
[11] Wente and Thuras, *Jour. A.I.E.E.*, Jan. 1934.
[12] Hilliard, J. K., *Tech. Bul. Acad. Res. Coun.*, Mar. 1936.

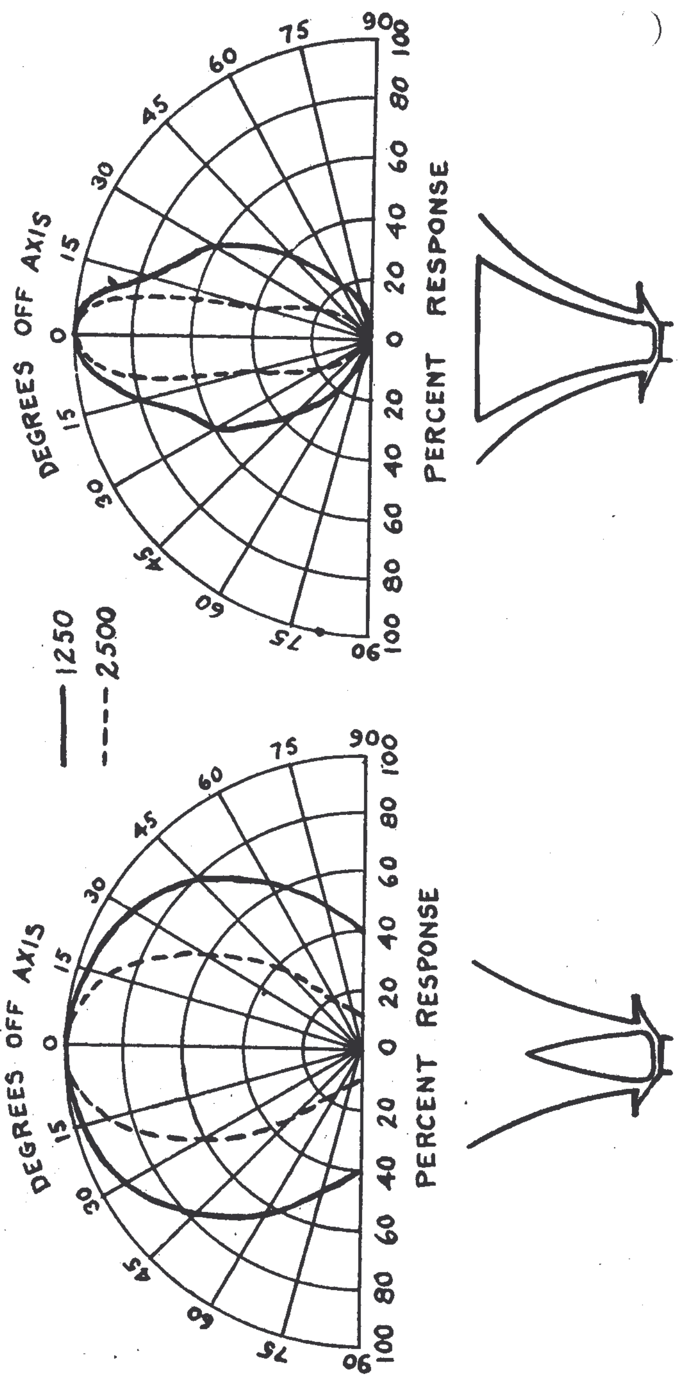


Fig. 8—Comparison of the directional characteristics of a ring-shaped mouth horn with that of a conventional horn having the same rate of flare and mouth area.

The dir)ional characteristics of the cellular horn shown in Figure 9 are shown in Figure 10. Above 2,000 cycles the dimensions of the total mouth surface are several wavelengths and the directional characteristics are uniform and defined by the total angular spread. Where the dimensions are comparable to the wavelength, the directional characteristics become very sharp, as shown by the polar curves for 500 and 1,000 cycles. Then as the dimensions of the surface become smaller than the wavelength (250 cycles) the angular spread broadens, as is illustrated by the larger spread for the smaller vertical dimension when compared to the smaller spread for the larger horizontal dimension.

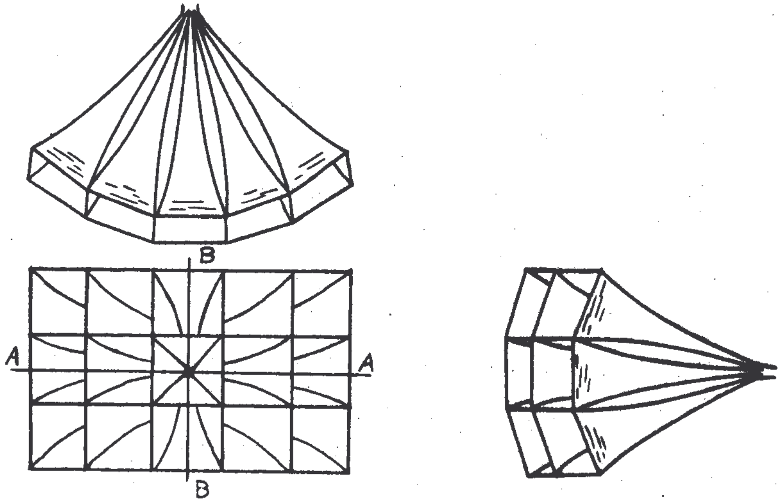


Fig. 9—Multi-horn loud speaker consisting of 15 individual exponential horns.

The directional characteristics of a multi-horn loud speaker may be predicted theoretically from the directional characteristics of an individual horn and the geometrical configuration of the assembly of horns. Assume that the point of observation is located on the *OY* axis, Figure 11, at a distance several times the length of the horn. The amplitude of the vector contributed by an individual horn for the angle ϕ can be determined from its individual directional characteristic. In this illustration, the plane $X'\ O'\ Z'$ is chosen as reference plane for the phase of the vector. The phase angle of the vector associated with an individual horn is

$$\theta = \frac{d}{\lambda}\ 360° \qquad (8)$$

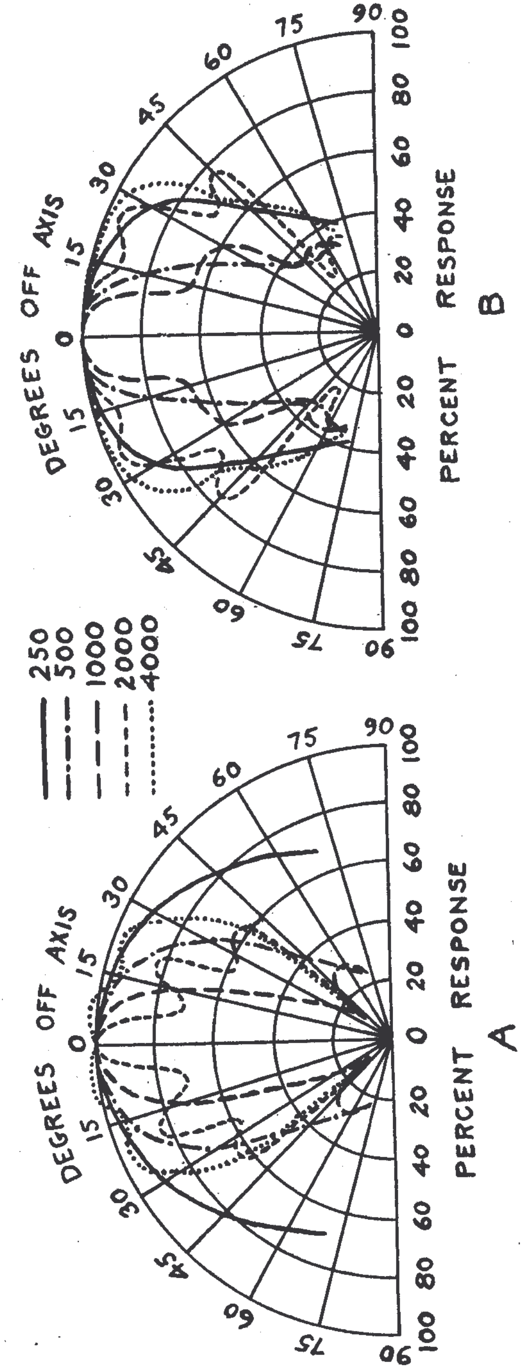


Fig. 10—Directional characteristics of the multi-horn loud speaker of Figure 9. A — vertical plane *B-B*. *B* — horizontal plane, *A-A*, of Figure 9.

where $d =$ the distance between the center of the mouth of the horn and the reference plane $X' O' Z'$,

$\lambda =$ wavelength.

The vectors, having amplitudes A_1, A_2, A_3, A_4, etc., determined from the directional characteristics and having phase angles θ_1, θ_2, θ_3, θ_4, etc., determined from Equation 8, are added vectorially as shown in Figure 11. This method of predicting the directional characteristics assumes that there is no interaction between individual horns which

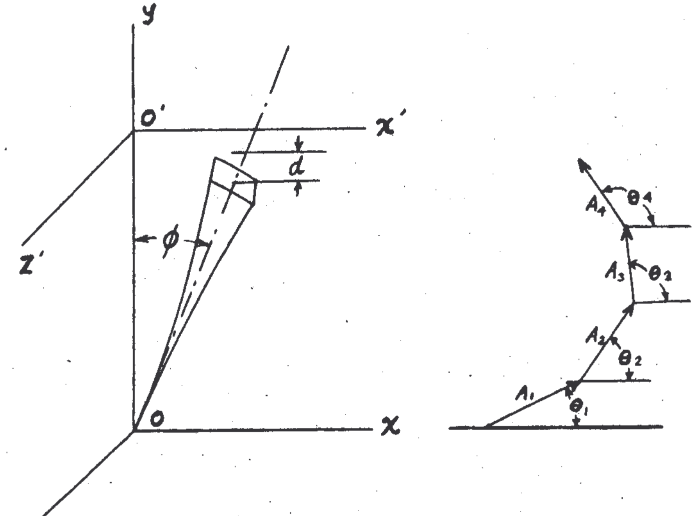


Fig. 11—Geometry for predicting the directional characteristics of a cluster of small horns.

changes the complexion of the velocities at the mouth from that which obtains when operating as an individual horn. Obviously, this condition is not absolutely satisfied. Apparently, the discrepancy has no practical significance because it has been found that this method of analysis agrees quite well with experimental results.

Analysis of this type shows that a combined mouth surface large compared to the wavelength is required to obtain uniform directional characteristics. It also shows that when the dimensions of the surface are comparable to the wavelength the directional pattern is relatively narrow. Furthermore, as would be expected, the directional characteristics are comparatively broad when the dimensions of the surface are small compared to the wavelength.

capacity can be a full quarter of a wavelength long ( )the closed-end type, and a full half of a wavelength long for the open-end type, as shown in Figure 5. The capacity per unit length of these line circuits can be varied without changing their overall length because the distributed inductance per unit length changes proportionally. For instance, the diameter of the small center tubing in the line circuits shown in Figure 5 could be increased until the radial clearance to the outer tubing is no more than the separation between the plates of the midget variable condenser shown in the picture, and the line circuits would still be a quarter of a wavelength and half of a wavelength long, respectively.

At the ultra-high frequencies the tube and its external circuit should be considered as integral parts of the electrical circuit. The interelectrode tube capacities and the inductance of the tube leads are a large portion of the total capacity and inductance of the electrical circuit. In order to attain the maximum overall size of the circuit, the tube elements should constitute a portion of a transmission line circuit which may be extended outside the tube. This ideal is difficult to achieve because of the close spacing required between the cathode, grid, and plate, and the larger spacing required between the leads to the electrodes to allow for insulation clearances, glass seals, neutralization circuits, and any other circuit irregularity. The desirable condition of uniformly distributed inductance and capacity along the tube leads and active elements has been approached in the design of the RCA-888. Though the ideal is not attained the arrangement does make possible the use of larger transmission line circuits than with other tubes, and hence larger power at higher frequencies.

I wish to acknowledge the many contributions of those associated in the work of developing these tubes and especially the help of Mr. J. B. Fitzpatrick who aided greatly by solving many of the basic problems of manufacture.

HORN LOUD SPEAKERS

By

HARRY F. OLSON

RCA Manufacturing Company, Inc., Camden, N. J.

PART II. EFFICIENCY AND DISTORTION[1]

INTRODUCTION

LARGE scale reproduction of sound involving several acoustical watts output is becoming quite commonplace. Since high power amplifiers are costly, it is logical to reduce the amplifier output to a minimum by the use of high efficiency loudspeakers. At the present time horn loudspeakers seem to be the only satisfactory high efficiency system for large-scale reproduction. For applications requiring high quality reproduction of intense sound, some consideration should be given to the introduction of frequencies not present in the output due to nonlinearity of the operating characteristics of the elements which constitute the vibrating system of the loudspeaker. It is the purpose of this paper to consider some of the factors which influence the efficiency and distortion characteristics of a horn loudspeaker.

EFFICIENCY

The absolute efficiency of a loudspeaker is the ratio of the useful acoustical power radiated to the electrical power supplied to the load, the current wave of which exercises a controlling influence on the shape of the sound pressure. This definition of efficiency excludes all incidental power supplied for such purposes as transformer losses, field excitation, etc. Sometimes another definition[2] is used involving both the vacuum tube and the loudspeaker. However, at the present time, there are many types of power vacuum tubes, ranging from those designed to feed into a load greater than the internal impedance of the tube to those designed to feed into a load smaller than the internal impedance of the tube. Therefore, in order to simplify the following discussion, the absolute efficiency will be used rather than the definition involving the vacuum tube.

The absolute efficiency[3] of a loudspeaker may be expressed as,

$$EFF = \frac{r_{em}}{r_{em} + r_{ed}} \qquad (1)$$

where, r_{em} = motional resistance, ohms,
r_{ed} = damped resistance of the voice coil, ohms,

[1] Part I, Impedance and Directional Characteristics, RCA REVIEW, April, 1937.
[2] Olson and Massa, Applied Acoustics, P. Blakiston's Son & Co., Philadelphia, p. 253.
[3] Kennelly and Pierce, *Proc. A.A.A.S.* Vol. 48. No. 6. 1912.

The motional resistance of the mechanical system of a dynamic loudspeaker is the real part of,

$$z_{em} = \frac{(Bl)^2}{z_m} \times 10^{-9} \text{ ohms} \qquad (2)$$

where, B = flux density, gausses,
l = length of wire in the voice coil, centimeters,
z_m = mechanical impedance of the vibrating system at the voice coil, mechanical ohms.

This expression of efficiency assumes[4] that no energy is lost in the form of mechanical hysterisis, but that all of the motional resistance is due to useful acoustic radiation and that the force factor is real.

Equation 2 may also be used to determine the efficiency of a loudspeaker experimentally. As in all tests of this kind care must be taken to obtain conditions which will insure the validity of the measurements.

Horn loudspeakers are usually of the dynamic type incorporating features which result in high efficiency. Therefore Equation 2 may be used to predict the efficiency and performance quite accurately. It is the purpose of this section to consider the performance of horn loudspeaker systems using the motional resistance method as a basis for comparison. The principal parameters which govern the performance are the horn dimensions, the diaphragm area, mass and suspension stiffness, the voice coil, the flux density and the air chamber coupling the diaphragm to the horn.

The first consideration will be a simple system consisting of a dynamically-driven diaphragm coupled to a horn having a throat impedance which is an acoustic resistance of constant value. To further simplify the problem, the stiffness of the diaphragm suspension will be considered negligible and the capacitance of the air chamber will be assumed to be zero. The problem is to consider the efficiency of the loudspeaker as a function of the throat dimensions.

The expression for the efficiency of this system is given by,

$$EFF = \frac{42(Bl)^2 A_D^2 A_T}{r_{ed}\,[(42A_D^2)^2 + (\omega m A_T)^2]\,10^9 + 42(Bl)^2 A_D^2 A_T} \qquad (3)$$

where, A_D = area of the diaphragm, square centimeters,
A_T = area of the throat, square centimeters,
m = mass of the diaphragm and voice coil, grams.

[4] In all of the systems considered in this section, the radiation from the free or open side of the diaphragm has been neglected. In certain cases at the higher frequencies this may be of the order of several per cent of the total output. For a consideration of the air-load on the back or open side of the diaphragm see H. F. Olson, *Jour. Acous. Soc. Amer.* Vol. 2, No. 4, p. 485.

To illustrate the relations between the various factors in Equation 3 the efficiency characteristics, for various loads upon a diaphragm driven by an aluminum coil of equal mass operating in a field of 22000 gausses, are shown in Figure 1. These data show that it is comparatively simple to obtain high efficiencies at the lower frequencies. However, at the higher frequencies the efficiency is limited by the mass of the diaphragm and voice coil. In this example the mass of the diaphragm has been chosen equal to the mass of the coil. It has been found that a diaphragm lighter than the voice coil is usually too fragile to be of value and these results represent the practical limit of mass reduction.

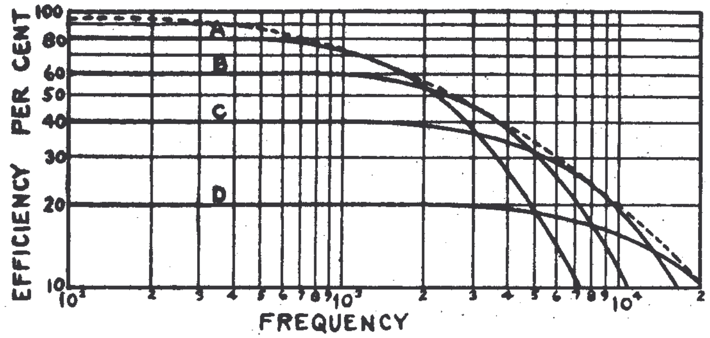


Fig. 1—Efficiency characteristic of a 1-gram aluminum voice coil, in a 22000-gauss field, driving a 1-gram diaphragm. The graphs are for the following values of mechanical resistances presented to the diaphragm: A, 16000; B, 42000; C, 96000; D, 254000 mechanical ohms. Dotted curve shows the maximum efficiency possible at each frequency.

The data of Figure 1 show that, to obtain the maximum efficiency[5, 6, 7, 8] over a wide frequency range with a system of this type, it is advantageous to use two or more units, each one designed for maximum efficiency over the frequency range which it supplies.

The equivalent electrical circuit and typical efficiency characteristic of a system of a single degree of freedom, consisting of a tuned cone coupled to a large throat horn, is shown in Figure 2. High efficiency is obtained over a relatively narrow range. Such a system may be used for speech reproduction. However, a "broader" frequency characteristic which may be obtained with two or more degrees of freedom results in more natural reproduction and better articulation.

[5] Hanna, C. R., *A.I.E.E.* Vol. 47, No. 4, p. 253.
[6] Wente and Thuras, *A.I.E.E.* Vol. 53, No. 1, p. 17.
[7] Olson and Massa, *Jour. Acous. Soc. Amer.* Vol. 8, No. 1, p. 48.
[8] Massa, F. *Jour. Acous. Soc. Amer.* Vol. 8, No. 2, p. 126.

A system of two degrees of freedom, consisting of a dynamically driven tuned diaphragm coupled by means of an air chamber to a horn, is shown in Figure 3.

The acoustic impedance at p is given by,

$$z = \frac{z_1 z_2 + z_1 z_3 + z_2 z_3}{z_2 + z_3} \qquad (4)$$

where $\quad z_1 = j\omega M + \frac{1}{j C_1}$

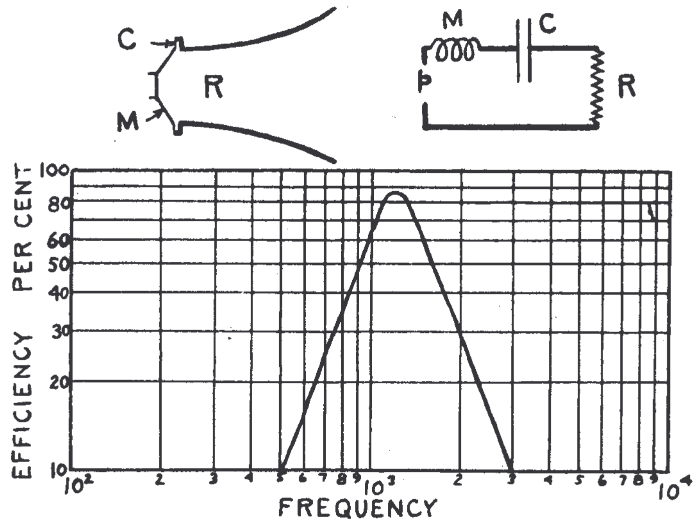


Fig. 2—Efficiency characteristic of a system of a single degree of freedom.

$$z_2 = \frac{1}{j\omega C_2}$$

$z_3 = R$
M = inertance of the cone,
C_1 = capacitance of the diaphragm suspension system,
C_2 = capacitance of the air chamber,
R = horn throat acoustic resistance.

The efficiency of this system may be predicted by means of Equations 1, 2, and 4. A typical efficiency characteristic of two degrees of freedom is shown in Figure 3. A loudspeaker having this type of efficiency characteristic has been found to be useful for speech reproduction at very high sound levels.

The results shown in Figure 1 were obtained by assuming the capacitance of the air chamber to be zero. In general, it is impractical to design a high efficiency loudspeaker to cover a wide frequency range without an air chamber, because the diaphragm is usually larger than the throat. However, the addition of an air chamber[9, 10, 11, 12] is actually an advantage because the efficiency may be increased over a wide frequency band by employing an appropriate design. The air chamber introduces a capacitance in parallel with the horn throat impedance which reduces the effective reactance of the vibrating system. The

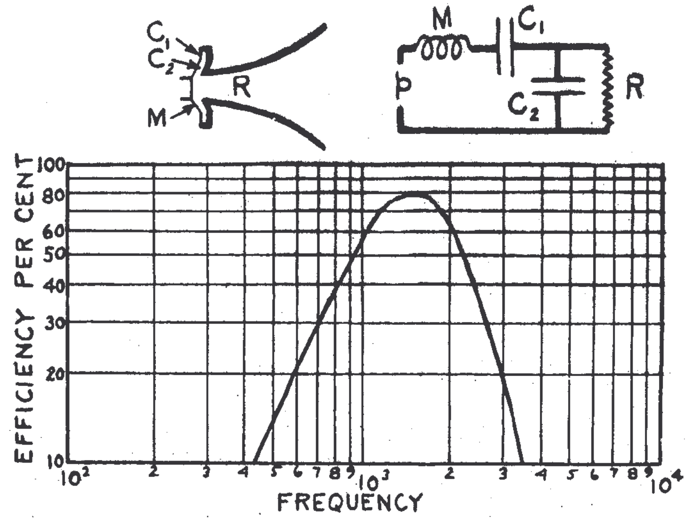


Fig. 3—Efficiency characteristics of a system of two degrees of freedom.

efficiency characteristic of a horn loud speaker with and without an air chamber is shown in Figure 4. These results show that the efficiency is substantially increased over a range of two octaves by the introduction of an air chamber. Due to the sharp high frequency cut-off the air chamber should be designed so that this occurs at the upper frequency limit of the reproducing system.

The results shown in Figures 3 and 4 indicate that the effective mass of the vibrating system may be reduced and the response increased by means of a multi-resonant system. This method provides a means for reducing the effective mass and for improving the efficiency.

---

[9] Hanna and Slepian, *A.I.E.E.* Vol. 43, No. 3, p. 251.
[10] Wente and Thuras, *Bell System Tech. Jour.* Jan. 1928, p. 140.
[11] Olson, H. F. *Jour. Acous. Soc. Amer.* Vol. 2, p. 242.
[12] Wente and Thuras, *A.I.E.E.* Vol. 53, No. 1, p. 17.

The vibrating systems considered in this section have employed aluminum voice coils operating in an air gap of 22000 gausses and driving either fibre, paper, bakelite or aluminum-alloy diaphragms. These materials represent the practical limit for obtaining high efficiencies at the present time. When new materials are developed which will permit an increase in the air-gap flux density or a reduction in mass of the diaphragm or a reduction in the resistance-density product of the voice coil it will be possible to improve the efficiency.

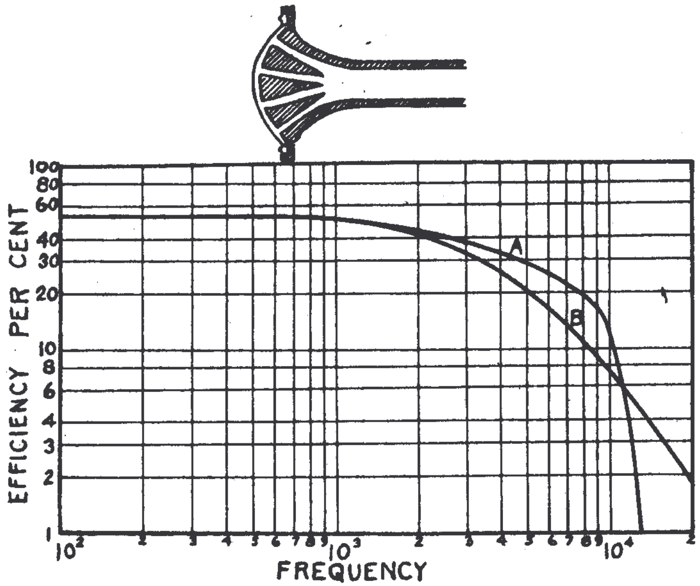


Fig. 4—A, Efficiency characteristic of a diaphragm coupled to a horn by means of an air chamber of the type shown. B, Efficiency characteristic in the absence of an air chamber. The air chamber shown consists of annular slits coupling the diaphragm to the horn throat. The same increase in efficiency can be obtained with other designs—for example, a series of cylindrical holes coupling the diaphragm to the horn.

The voice coil, in high-power loudspeakers may run at a very high temperature which results in a reduction of efficiency. The damped resistance is given by,

$$r_{ed} = (1 + kt)\, r_{edo} \qquad (5)$$

where $k = .0042$
$t =$ temperature centigrade
$r_{edo} =$ resistance at 0° C.

The efficiency as a function of the temperature, for various initial efficiencies at 20° C, is shown in Figure 5. These results show that the

effect of temperature in reducing the efficiency is most pronounced in loudspeakers of low efficiency.

Distortion and Overload

It is the purpose of this section to consider some types of amplitude distortion which may occur in horn loudspeakers together with factors which determine the loudspeaker rating.

In general, a sound wave of large amplitude cannot be propagated in air without a change in wave form and as a result the production of harmonics. If equal positive and negative changes of pressure are impressed upon a mass of air the changes in volume of the mass will not be the same. The volume-change for an increase in pressure will be less than the volume-change for an equal decrease in pressure. Physically, the distortion may be said to be due to the non-linearity of air.

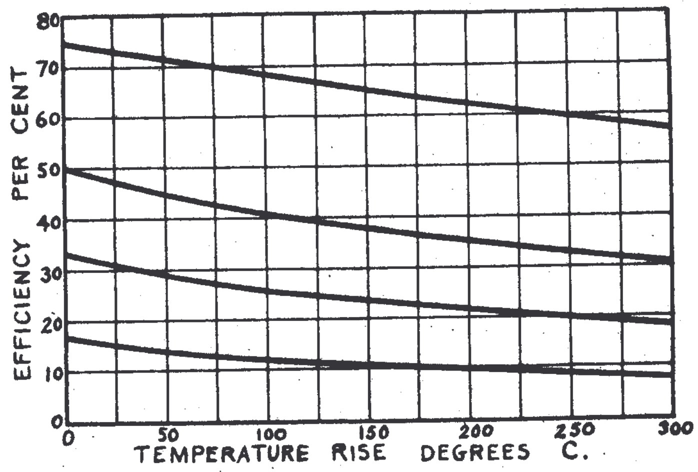


Fig. 5—The effect of temperature rise upon the efficiency of a loud speaker, with an aluminum voice coil, having the indicated initial efficiencies. Initial temperature 20° C.

The magnitude of the harmonic frequencies may be obtained theoretically from the differential equation of wave propagation. Rocard[13] was the first to investigate the generation of harmonics in an exponential horn. The subject was later investigated theoretically and experimentally by Thuras, Jenkins and O'Neil[14] and theoretically by

[13] Rocard, *Comptes Rendus*, Vol. 196, p. 161, 1933.
[14] Thuras, Jenkins and O'Neil, *Jour. Acous. Soc. Amer.* Vol. 6, p. 173, 1935.

Goldstein and McLachlin[15]. For constant sound-power output the distortion is proportional to the square of the frequency. Further, the nearer the observation frequency is to the cut-off frequency the smaller the distortion. For this reason there is an advantage in the use of two or more units dividing the range into two or more parts.

The distortion due to non-linearity of the air is, at the present time, one of the most important as well as troublesome factors in the design of high efficiency loudspeakers for large outputs. In order to obtain high efficiency, particularly at the higher frequencies, it is necessary to couple the relatively heavy diaphragm to a throat having an area

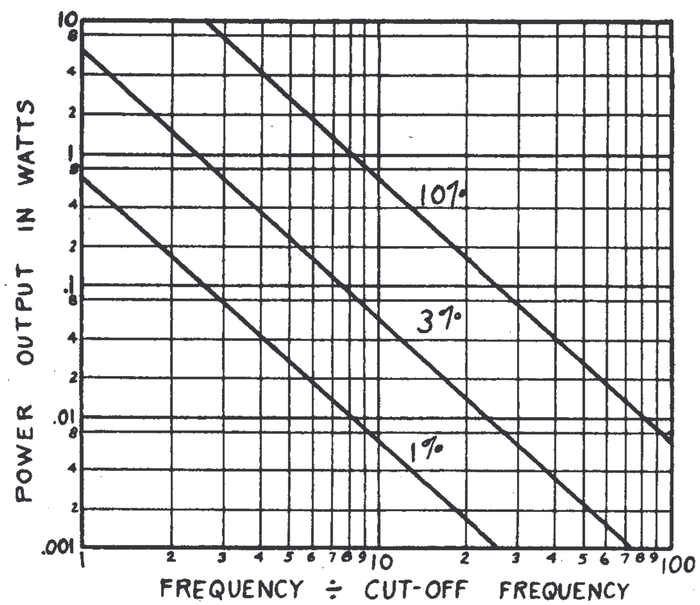


Fig. 6—The power output of infinite exponential horns, per square centimeter of throat area, for 1, 3 and 10 per cent distortion, as a function of the ratio of the frequency under consideration to the cut-off frequency.

small compared to the diaphragm. On the other hand, for certain allowable distortion the power output is directly proportional to the area of the throat. As a consequence, to deliver large outputs at high efficiencies requires a very large throat which may be suitably coupled to a correspondingly large diaphragm or a large number of lightly driven small throat units.

The power which can be transmitted per square centimeter of throat area of an infinite exponential horn, as a function of the ratio of the

[15] Goldstein and McLachlin, *Jour. Acous. Soc. Amer.* Vol. 6, p. 275, 1935.

frequency under consideration to the cut-off frequency, with the production of 1, 3 and 10 per cent distortion is shown in Figure 6. For sake of generality the curves shown in Figure 6 refer to an infinite horn. Furthermore, the increase in power which may be transmitted by a practical finite horn is only a few per cent greater than that shown in Figure 6.

In practical applications the distortion due to the nonlinearity of the air is most important in theatre reproduction where high-power, wide-range loudspeakers with small distortion are required. The permissible distortion is usually placed at 3 per cent. The average throat area of commercial high-frequency loudspeakers, available to-day, of the type shown in Figure 9 of Part I is approximately 10 sq. cm. The power which this loudspeaker can deliver with 3 per cent distortion is 10 times the value shown in Figure 6. For a cut-off of 200 cycles the power output is 10 watts at 500 cycles, 2.5 watts at 1000 cycles, .6 watts at 2000 cycles, etc. Taking into account the energy distribution of speech and music as a function of the frequency, this distortion characteristic has been found to be satisfactory at the present time.

In general, acoustic and electrical networks are assumed to be invariable; that is, the constants and connections of the network or system do not vary or change with time. A network which includes a circuit element that varies continuously or discontinuously with time is called a variable network. In some cases the variable elements are assumed to be a certain function of the time; that is, the variations are controlled by outside forces which do not appear in the equations or statement of the problem. In another type of variable-circuit element the variation is not an explicit time function, but a function of the current (and its derivatives) which is flowing through the circuit.

An example of the latter type of variable-circuit element in an acoustical system is the air-chamber capacitance in a horn loudspeaker. The excursions of the diaphragm changes the capacitance. The acoustic capacitance of the air chamber, Figure 7, is given by,

$$C = \frac{V}{\rho c^2} = \frac{A(d+x)}{\rho c^2} \tag{6}$$

where
ρ = density of air, grams per cubic centimeter,
c = velocity of sound, centimeters per second,
V = volume of the air chamber, cubic centimeters,
A = projected area of the air chamber upon the diaphragm, sq. cm.
d = distance between the diaphragm and front boundary of the air chamber in the absence of motion, centimeters,
x = displacement of the diaphragm, centimeters.

In general, the distortion which this variable element introduces is small because for constant-sound output the amplitude of the diaphragm is inversely proportional to the frequency. At the low frequencies where the amplitude of the diaphragm may be so large that the volume becomes alternately zero and two times the normal volume the reactance of the capacitance is very small compared to the resistance. At the high frequencies where the reactance of the capacitance is comparable to the resistance, the amplitude of the diaphragm for the same output is so small that the variation in capacitance may be neglected. However, the picture is changed somewhat when both a high and a low frequency are impressed upon the system. Under these conditions considerable change in capacitance occurs due to the large amplitude of the diaphragm for the impressed low-frequency. The

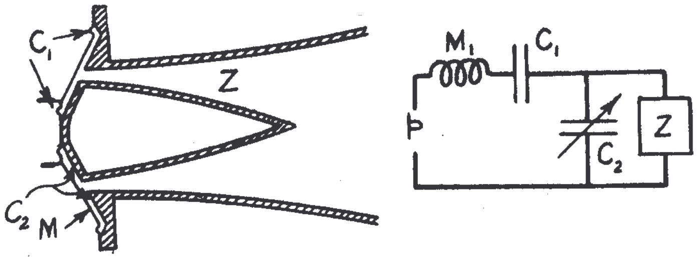


Fig. 7—A mechanism with an air chamber coupling the diaphragm to the horn. The variation in volume of the air chamber introduces a non-linear element in the form of the capacitance C_2. The equivalent electrical circuit indicates the effect of the non-linear element upon the system.

resultant change in capacitance introduces a variable element, for the impressed high-frequency, which may have variations in impedance as large as the impedance of the other elements of the system. When this condition obtains, particularly with close spacing between the diaphragm and front boundary of the air chamber, the distortion may be tremendous.

In the above discussion the air chamber is assumed to be a pure capacitance. This assumption is not correct at the higher frequencies where the dimensions of the air chamber are comparable to the wavelength. Regardless of the form of this impedance, it is nevertheless a function of the spacing between the diaphragm and the air chamber and is therefore a non-linear element.

The outside diaphragm suspension is another example of a variable-circuit element in an acoustic system. In certain types, or as a matter of fact, for unlimited amplitudes in all types of suspension systems, the stiffness is not a constant, but a function of the amplitude and in general increases for the larger amplitudes.

In the case of a horn loudspeaker the velocity of the diaphragm for constant sound output is independent of the frequency. Under the same conditions the amplitude is inversely proportional to the frequency. Consequently, the greatest distortion due to the suspension system will occur at the low-frequency end of the working range.

In many suspension designs, including paper, fiber and metal diaphragms, considerable distortion occurs at the lower frequencies. To test for this type of distortion a large throat and air chamber should

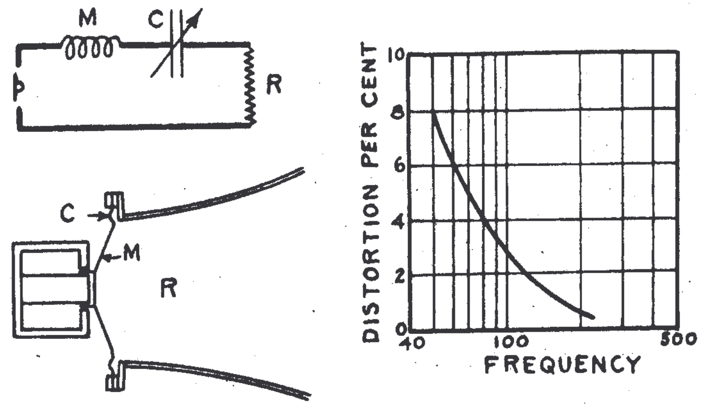


Fig. 8—Mechanism having a diaphragm with a non-linear suspension system. Equivalent electrical circuit of the vibrating system indicates the effect of the non-linear element. Graph shows a typical distortion characteristic obtained on an 8" diaphragm feeding 5 watts to a large throat horn. A large throat horn is used to minimize distortion due to the air chamber and non-linearity of the air.

be used to reduce the error due to non-linearity of the air and variation in the capacitance of the air chamber. The system and method is shown in Figure 8. The amount of distortion introduced by the suspension system when it is coupled in the normal manner to a smaller throat can be computed from the results obtained on the larger throat. The results in Figure 8 show that considerable distortion may occur if an improperly designed suspension is used. Of course, these values will be relatively reduced when referred to the smaller throat.

Inhomogeneity of the flux density through which the voice coil moves is another source of distortion. The result is that the driving force does not correspond to the voltage developed by the generator in the electrical driving system. Furthermore, the motional impedance is a function of the amplitude. This type of distortion can be eliminated by making an air gap of a sufficient axial length so that the voice coil remains at all times in a uniform field. This type of distortion can also be eliminated by making the voice coil longer than the air gap so that the summation of the products of each turn and the flux density is a constant.

The distortions referred to above have been concerned with higher harmonics; that is, multiples of the fundamental. It has been analytically shown by Pederson[16] that subharmonics are possible in certain

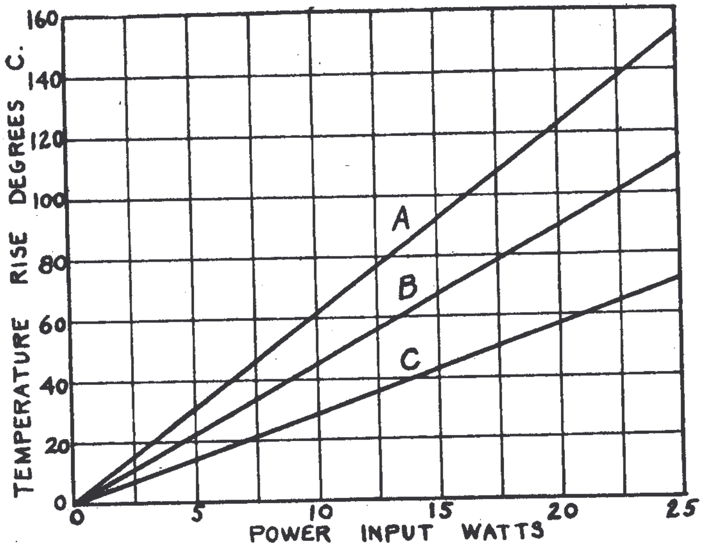


Fig. 9—The temperature rise as a function of the power delivered to a voice coil for air gap clearances, as follows: A, .021". B, .015". C, .009". Coil 1½" diameter and 0.25" length.

vibrating systems. The existence of subharmonics in direct radiator loudspeakers is quite well known. However, in horn loudspeakers the diaphragms are relatively small and quite rigid. Consequently the conditions for the production of subharmonics are not particularly favorable. Nevertheless in certain horn loudspeakers subharmonics can be produced when the diaphragms are driven with large inputs. It has been noticed that by impressing a steady tone upon a system which produces both subharmonics and higher harmonics that the subharmonics are more pronounced and objectionable to the ear than the higher harmonics. However, by actual measurement under these conditions the subharmonic was less than one per cent, while the higher

[16] Pederson, P. O. *Jour. Acous. Soc. Amer.*, Vol. 6, p. 227, 1935.

harmonics were several per cent of the fundamental. The explanation appears to be that it is more difficult to mask a low tone with a high tone than the reverse procedure. Another feature of subharmonic phenomena is the relatively long time required for "build up". Conventional sound reproduction does not usually require the reproduction of a single isolated high frequency tone of long duration. Furthermore, as pointed out above, with relatively small rigid diaphragms and large resistive loads the production of subharmonics is quite small. Therefore, at the present time it seems that subharmonic distortions in horn loudspeakers are not as troublesome nor as important a problem as the other types discussed above.

The maximum allowable distortion may determine the power rating for the loudspeaker. However, in certain loudspeakers the maximum allowable temperature of the voice coil determines the power rating. This is particularly true of high frequency horn loudspeakers.

By making the efficiency a maximum, the dissipation in, and the resulting temperature of, the voice coil for a certain acoustic output will be a minimum. Practically all the heat energy developed in the voice coil is transmitted across the thin air film between the voice coil and the pole pieces and from the pole pieces to the field structure and thence into the surrounding air. In this heat circuit practically all the drop in temperature occurs in the thin air film. The temperature of the voice coil approaches the temperature of the pole pieces as the thickness of the air film is decreased. The temperature rise as a function of the power dissipated in the voice coil for various clearances between the voice coil and pole pieces is shown in Figure 9. These results are obtained for no motion of the voice coil. When motion occurs, the thermal impedance of the air film is reduced and the temperature of the voice coil is diminished.