A Compound Horn Loudspeaker

HARRY F. OLSON AND FRANK MASSA, *RCA Manufacturing Company, Camden, N. J.*
(Received March 2, 1936)

A new type of loudspeaker is described in which a single mechanism is coupled to two horns: a straight axis high frequency horn and a folded low frequency horn. A theoretical analysis of the combined system is given and experimental data are shown which indicate smooth uniform response from 50 to 9000 cycles, and an efficiency of the order of 50 percent over a large portion of this range.

INTRODUCTION

THE advantages of horn type loudspeakers over the direct radiator flat baffle type are, in general, well recognized. In spite of the inherent advantages of a horn type loudspeaker, it has not found as widespread an application as would be expected, primarily because of the awkward bulk that a horn presents. To circumvent the objections introduced by a straight axis horn, the first natural attempt was to coil the horn into some convenient shape. It is known, however, that this procedure is accompanied by a loss of high frequencies depending on the amount of destructive interference incurred by folding. Since the length of a horn must increase as the frequency limit of reproduction decreases, it becomes obvious that a long horn can be folded if it is to be used to reproduce only the lower end of the frequency spectrum and the higher frequencies can be reproduced through a straight axis short horn. A combination of low frequency folded horns and high frequency straight horns has already been successfully employed in theater equipment, each horn requiring a separate driving mechanism.

It is the purpose of this paper to describe what is termed a compound horn loudspeaker consisting of a single mechanism with one side of the diaphragm coupled to a short straight axis horn and the other side coupled to a long folded horn whose mouth terminates in an annular opening surrounding the high frequency horn. This compound horn has the advantage that only a single mechanism is required to feed the two horns and also that both horns are built into a single compact unit.

THEORY[1]

The most popular horns for the production of sound are the conical and exponential, both of which will be described briefly.

A horn in which the flaring is given by

$$S=(S_0/X_0^2)X^2, \tag{1}$$

where S_0 is the throat area at X_0 and S the area at any distance X along the axis, is termed a conical horn.

A horn in which the flaring is given by

$$S=S_0e^{mX} \tag{2}$$

is termed an exponential horn (m is known as the flaring constant).

There are a large number of significant differences between conical and exponential horns. The fundamental difference is the shape of the throat resistance characteristic.

The throat acoustic resistance of an infinite conical horn is given by

$$r=(\rho c/S_0)k^2X_0^2/(1+k^2X_0), \tag{3}$$

where ρ=density of air, c=velocity of sound, $k=2\pi/\lambda$, λ=wave-length. The other quantities have been defined above.

The throat acoustic resistance of an infinite exponential horn is given by

$$r=(\rho c/S_0)(1-m^2/4k^2)^{\frac{1}{2}}, \tag{4}$$

where m is the flaring constant.

Fig. 1 shows the resistance characteristic of an infinite conical and exponential horn. It will be seen that the exponential horn has a definite cut-off frequency above which the resistance increases

[1] For a detailed analysis of various shapes of horns as well as a complete bibliography relating to horns, see Olson and Massa, *Applied Acoustics* (Blakiston, Philadelphia), pp. 43 to 49 and 181 to 197.

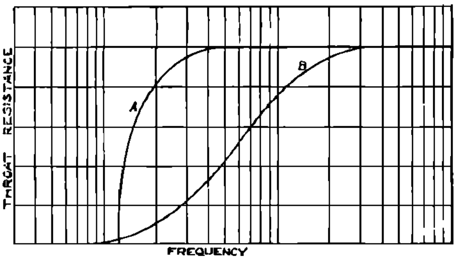


FIG. 1. Throat acoustic resistance of infinite horns. A. Exponential. B. Conical.

rapidly and becomes constant. For frequencies below $2\omega = mc$, the horn transmits nothing. In other words the infinite exponential horn behaves as a high pass filter. The definite cut-off of the exponential horn has been found to be useful in obtaining uniform response in the overlap region of the low and high frequency horns of the compound horn.

The above conclusions are somewhat altered by the substitution of finite for the infinite horns. The difference will depend upon the discrepancy between the surge impedance of the horn at the point of introduction of the mouth and the mouth impedance looking outward.

The throat acoustic impedance of a finite exponential horn is given by

$$Z_1 = \frac{\rho c}{S_1} \frac{Z_2 \cos(bl-\theta) + j(\rho c/S_2)\sin(bl)}{jZ_2 \sin(bl) + (\rho c/S_2)\cos(bl+\theta)}, \quad (5)$$

$$\theta = \tan^{-1}(a/b),$$

where $a = -m/2$, $b = \frac{1}{2}(4k^2 - m^2)^{\frac{1}{2}}$, l = length of horn, Z_2 = mouth acoustic impedance of horn.

In theoretical considerations of exponential horns there is always some question as to the nature of the mouth impedance. In the case of the compound horn which we will consider, this is fairly easily solved. The large horn is sufficiently close to the floor to consider the solid angle into which it feeds to be 2π. The small horn is surrounded by a baffle and its mouth then feeds into a solid angle of 2π.

Under these conditions the resistive component of the mouth acoustic impedance is

$$r_2 = (\rho c/\pi R^2)(1 - J_1(2kR)/kR). \quad (6)$$

The reactive component is

$$X_2 = (\rho c/\pi R^2)(K_1(2kR)/2k^2R^2), \quad (7)$$

where $R = (S_2/\pi)^{\frac{1}{2}}$, J_1 and K_1 are Bessel functions. The acoustic impedance Z_2 for the mouth of the horn is

$$Z_2 = r_2 + jX_2. \quad (8)$$

The choice of the throat dimensions to obtain maximum efficiency with an exponential horn depends on the mass of the cone and voice coil and the area of the cone. This may be illustrated by considering a cone of mass m coupled to throat of acoustic resistance r_A.

The motional resistance of this system is

$$r_{eM} = \text{real part of } (Bl)^2/Z_M \text{ abohms}, \quad (9)$$

where $Z_M = r_A A_c^2 + j\omega m = (42/A_T)A_c^2 + j\omega m$
A_c = area of cone in square centimeters,
A_T = area of throat,
m = mass of cone and coil in grams,
B = flux density,
l = length of the wire in the voice coil,
$\omega = 2\pi f$,
f = frequency.

The efficiency is

$$E_{ff} = r_{eM}/(r_{eM} + r_{ed}), \quad (10)$$

where r_{ed} = resistance of the voice coil in abohms.

From the foregoing analysis it will be seen that in order to obtain maximum efficiency the surge throat resistance should be comparable to the reactance of the vibrating system. In view of the fact that the mechanical impedance of the vibrating system increases with frequency, a small throat should be used at the higher frequencies and a relatively large throat at the lower frequencies. If a small throat is used for the entire frequency band, the maximum possible efficiency cannot be obtained at the lower frequencies because of the fact that the motional resistance reflected into the voice coil is reduced.

In Fig. 2 are shown several theoretical efficiency curves which were calculated to show the improvement in high frequency efficiency resulting from the use of smaller throats. These curves were computed for a 5-inch diameter cone having 280 inches of wire in the voice coil. The total mass of cone and coil is 2.5 grams, the coil resistance is 7 ohms and the air-gap density is 20,000 gauss. Assuming the cone to move as a piston, the efficiency was calculated for three cases, namely, feeding a horn having a 300 sq. cm throat, another with a throat of 50 sq. cm and

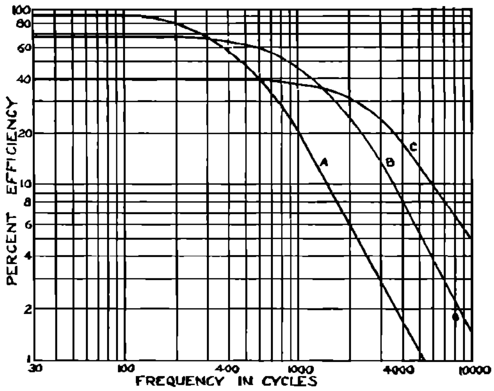


FIG. 2. Theoretical efficiency of a horn loudspeaker with various throat areas. *A*. 300 sq. cm; *B*. 50 sq. cm; *C*. 15 sq. cm.

finally feeding a horn with a throat area of 15 sq. cm.

From Fig. 2 it can be seen that there is a distinct advantage in the use of two horns—one with a small throat for the high frequency range and one with a relatively large throat for the low frequency range. It may be pointed out in passing that many high fidelity loudspeaker systems employing horns use two units, large throat for the low frequency range and small throat for the high frequency range.

In addition to the advantage of obtaining higher over-all efficiency by the use of two horns —there are such additional advantages as: reduction in harmonic distortion by keeping the working range near the cut-off of the horn; practically uniform directional characteristics due to mouth sizes more nearly comparable to the wave-length over the working range; and the possibility of obtaining large low frequency power output with relatively small amplitudes of the cone.

A compound horn is a term which is used to designate a system of two horns coupled to a single diaphragm. In the compound horn the advantages of a two-horn system are preserved while employing only a single diaphragm or driving system.

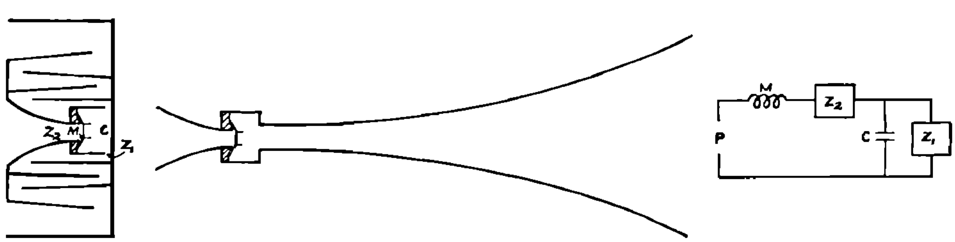
Fig. 3(a) shows a cross-sectional view of a compound horn loudspeaker. Fig. 3(b) shows the equivalent system in straight axis horns. Fig. 3(c) shows the equivalent electrical circuit of the acoustical system which in its simplest form consists of a dynamically driven cone M, a high frequency horn of impedance Z_2 at the throat, a low frequency horn of impedance Z_1 at the throat and an acoustic capacitance C.

The throat acoustic impedance characteristics of a typical compound horn computed from Eq. (5) are shown in Fig. 4.

It will be seen that below 330 cycles, the impedance of Z_2 both real and imaginary is zero and therefore there can be no dissipation in Z_2 below this frequency, which means that there can be no radiation from this horn below 330 cycles. The low frequency horn Z_1 cuts off at 42 cycles. This means that radiation will issue from Z_1 for all frequencies above 42 cycles provided energy is delivered to this horn. However, above 330 cycles the dissipation from Z_1 must be transferred to Z_2. This is partially accomplished by choosing the surge impedance of Z_2 large compared to Z_1 and, further, by introducing an acoustic capacitance C.

Going from the above word picture, the volume current in Z_1 is

$$U_1 = \frac{p/j\omega C}{\dfrac{j\omega M + Z_2}{j\omega C} + (j\omega M + Z_2)Z_1 + \dfrac{Z_1}{j\omega C}}. \quad (11)$$



a b c

FIG. 3. (a) Cross-sectional view of compound horn loudspeaker. (b) Equivalent of the compound horn loudspeaker showing the low frequency horn developed. (c) Equivalent electrical circuit of the dynamical system.

The volume current in Z_2 is

$$U_2=\frac{p(1/j\omega C+Z_1)}{\dfrac{j\omega M+Z_2}{j\omega C}+(j\omega M+Z_2)Z_1+\dfrac{Z_1}{j\omega C}}. \quad (12)$$

The dissipation or radiation of energy from Z_1 is

$$P_1=r_1U_1^2. \quad (13)$$

The radiation of energy from Z_2 is

$$P_1=r_2U_2^2 \quad (14)$$

where r_1 and r_2 are determined from Eq. (5) and plotted in Fig. 4 for a specific system of horns.

It will be noted that the impedance characteristic of Z_1 is nonuniform. However, it is interesting that with such wide variations in impedance characteristic, the maximum variation in energy output is 3 db. This is verified by measurements.

In the design of the compound horn, care should be taken that the phase of the volume currents issuing from the two horns is the same in the overlap region. This can be determined by a consideration of the expressions for the volume current at the mouths. See Eq. (5).

If further attenuation of the high frequency output of the low frequency horn above the overlap frequency is desired, an acoustic filter can be employed as shown in Fig. 5. If in Fig. 5, $M_c=M_2=\frac{1}{2}M_1=M$ and if $C_1=C_2=C$, then the cut-off frequency is

$$f=1/\omega(MC)^{\frac{1}{2}}. \quad (15)$$

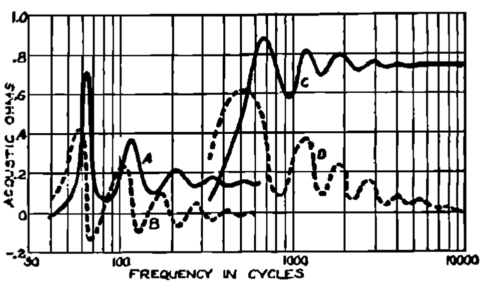


FIG. 4. Impedance characteristics of a compound horn. *A*. Throat acoustic resistance of low frequency section. *B*. Throat acoustic reactance of low frequency section. *C*. Throat acoustic resistance of high frequency section. *D*. Throat acoustic reactance of high frequency section.

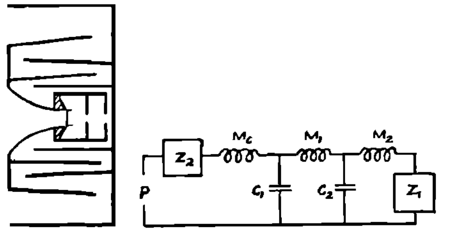


FIG. 5. A compound horn loudspeaker with an acoustic filter for causing a sharp cut-off of the low frequency horn. In the equivalent electrical circuit: Z_2, throat impedance of high frequency horn; M_c, inertance of cone; C_1, capacitance of cavity behind cone; M_1, inertance of first hole behind cone C_2, capacitance of volume between the holes; M_2, inertance of second hole; Z_1, throat impedance of low frequency horn.

Construction

The general construction of the compound horn loudspeaker is shown in Fig. 7. This construction results in a compact structure in which the entire volume is used for the loudspeaker. For the high frequency horn two types have been employed, namely the conical and exponential. The exponential yields smoother response and a definite low frequency cut-off. For the low frequency horn there are three possibilities shown in Figs. 6(a), (b), (c). In Fig. 6(a) is shown a true exponential horn of the folded type. Fig. 6(b) shows a first approximation employing a series of conical sections of different rates of flare and having a logarithmic flare expansion from section to section. Fig. 6(c) shows a second approximation employing straight cylindrical sections having logarithmic area expansion from section to section. Comparisons between the three types and a straight axis

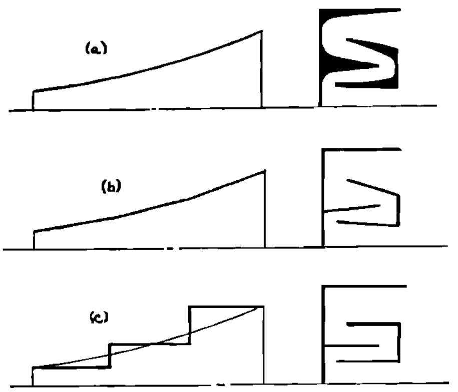


FIG. 6. (a) Constructional detail of a folded horn to give a true exponential flare. (b) Constructional detail of a folded horn which results in a series of conical flares that approximate an exponential flare. (c) Constructional detail of a folded horn which results in a series of abrupt changes in area whose average rate of change is an exponential curve.

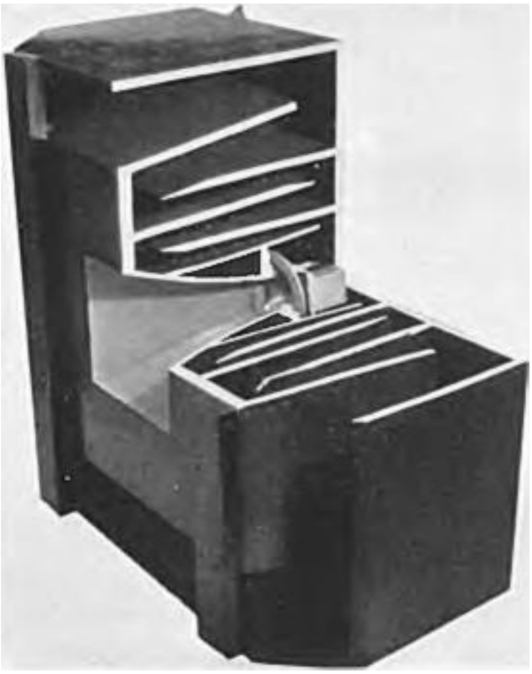


FIG. 7. Cut-away photograph of a compound horn loudspeaker.

exponential horn indicated very little difference below 300 cycles. In this range the wave-length is several times the length of each section and no deviation would be expected. Note that the cross section may be either square, rectangular or round, etc. The parameters referred to above are the area and the rate of increase in area.

A photograph of a compound horn loudspeaker employing an exponential high frequency horn and conical logarithmic expansion for the low frequency horn is shown in Fig. 7.

One-quarter of the horn has been cut away to show the construction. In this horn all the sections are square rather than cylindrical. This

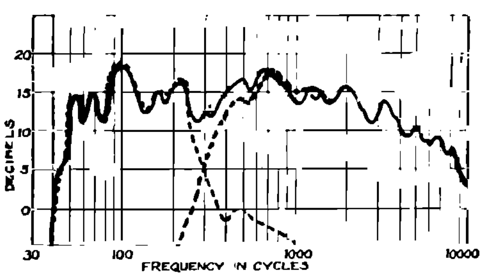


FIG. 8. Response-frequency characteristic of the compound horn shown in Fig. 7. Dotted curves show the response of the low and high frequency horns separately.

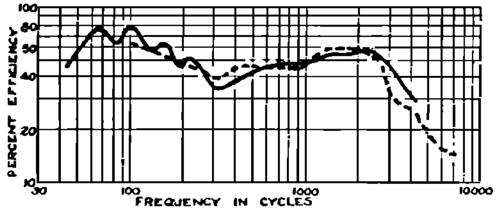


FIG. 9. Efficiency of the compound horn loudspeaker shown in Fig. 7. Solid curve obtained by the three-voltmeter method. Dotted curve obtained by the impedance bridge method.

is of no consequence—the important factor is the rate of area increase.

CHARACTERISTICS

The free space response frequency characteristic of a 40×40×17 inch compound horn is shown in Fig. 8. The dotted curves show the response of the low and high frequency sections separately. It will be seen that the response characteristic is quite smooth over the range from 50 to 9000 cycles.

The flux density in the mechanism was 20,000 gauss. The vibrating system consisted of a corrugated cone 5″ in diameter which was driven by an aluminum voice coil. The use of a corrugated cone results in high efficiency at the higher frequencies because of the reduction of the effective mechanical impedance. The efficiency of this loudspeaker was measured by two methods, namely the three-voltmeter method and an impedance bridge. The results are shown in Fig. 9 and indicate high efficiency. A conventional cone loudspeaker in a flat baffle has an efficiency of from two to five percent.

CONCLUSION

This paper has given the analysis of the compound horn loudspeaker and has shown the conditions that must be satisfied in order to obtain satisfactory performance. Under favorable conditions compound horn loudspeakers may be built to give uniform response up to 10,000 cycles and as low as is desired on the other end of the spectrum. The low frequency cut-off is only limited by the size of the horn or the power handling requirements. This wide range reproduction is obtained at efficiencies of the order of 50 percent over the greater part of the frequency range.