LOUDSPEAKER ENCLOSURE DESIGN

by E. J. Jordan

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1.—Alternative Methods: Their Advantages and Disadvantages

In the first part of this article the theory underlying the principal types of loudspeaker enclosure is reviewed, and formulae associated with the major design factors are given. This will be followed later by a discussion of some recent developments in which an improved low-frequency performance has been achieved in cabinets of relatively small volume.

The loudspeaker enclosure has the task of doing something (useful or otherwise) with the low-frequency radiation from the rear of the loudspeaker cone, which would otherwise cancel the radiation from the front of the cone.

Before examining various methods of overcoming this, let us establish the principles on which our future arguments will be based.

We shall regard the moving parts of a loudspeaker as a mechanical system which at low frequencies is analogous to an electrical circuit, as shown in its simplest form in Fig. 1.

The complete analogy is revealed by an examination of the electrical and mechanical equations viz.

\[
\text{Force} = M \frac{d^2S}{dt^2} + R \frac{dS}{dt} + SK
\]

\[
\text{E.m.f.} = L \frac{d^2Q}{dt^2} + R \frac{dQ}{dt} + \frac{Q}{C}
\]

where \( M \) = mass, \( L \) = inductance, \( S \) = displacement, \( Q \) = charge, \( C \) = capacitance, \( K \) = stiffness and \( R \) = resistance.

There are, of course, other analogies, but the above lends itself more readily to discussions of the proposed nature.

Assume for a moment that the loudspeaker is mounted on an infinite baffle. It will be seen, that the power developed in \( R_a \) (Fig. 1) is a function of the current through it. Comparing the above equations it will be seen that \( i \left( \frac{dQ}{dt} \right) \) is analogous to the cone velocity \( v \left( \frac{dS}{dt} \right) \). Hence it is the cone velocity, and not the displacement, that is responsible directly for the radiated output power, \( v^2 R_a \).

From this it would seem that, if the radiated power is to be independent of frequency, the resistive components of the circuit should be high relative to the reactive components. This is not so in practice, since at frequencies where the wavelength is longer than twice the cone diameter the value of \( R_a \) falls as the frequency is lowered. The reactance of \( M \) also falls, however, and the increasing velocity resulting from this may largely compensate for the fall in \( R_a \) to the extent that the radiation remains substantially constant, down to a frequency where \( \omega M \frac{1}{\omega C} \rightarrow 0 \). Here the velocity of the cone rises sharply, and is limited only by \( R_M \), \( R_a \), and \( R_M \). This produces an increase in the radiated power and is the resonant frequency of the loudspeaker.

Below this frequency, the impedance of the circuit rises as the frequency falls, due to the reactance of \( C \). Consequently the radiation falls very sharply. The resonant frequency may thus set the limit to the low-frequency response of the loudspeaker.

The above may be shown by considering the expression for the radiated power at the frequencies being discussed:

\[
P = v^2 R_a = \text{Force}^2 \frac{2 \pi f^2}{Z_m^2} \cdot \frac{2 \pi f^2}{c} \cdot (\pi r^2), \text{where } r \text{ is the radius of the cone.}
\]

Above resonance if \( R_M << X_m \) (mass)

\[
P \propto \frac{\text{Force}^2}{X_m^2} \cdot f^2
\]

This is the condition of mass control, and since \( X_m^2 \alpha f^2 \), \( P \) is independent of \( f \).

Above, at, or below resonance, if \( R_M >> X_m \) (stiffness)

\[
P \propto \frac{\text{Force}^2}{X_m^2} \cdot f^2 \alpha f^2
\]

This is the condition of constant velocity, and \( P \) falls with \( f \) at the rate of 6dB/octave.

Below resonance if \( R_M << X_m \) (stiffness),

\[
P \propto \frac{\text{Force}^2}{X_m^2} \cdot f^2 \alpha f^2
\]

This is the condition of constant amplitude and \( P \) falls with \( f \) at the rate of 12dB/octave.

Above resonance if \( R_M \) is comparable to \( X_m \)

\[
P \propto \frac{\text{Force}^2}{X_m^2} \cdot f^2
\]

and \( P \) falls with frequency at a rate determined by the ratio \( f^2 \frac{R_M^2 + X_m^2}{R_M^2} \).

In all cases the radiation resistance is small.

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relative to the total mechanical impedance of the system; its effect on the velocity has therefore been neglected.

So far it has been assumed that the loudspeaker is mounted in an infinite baffle. The analogous circuit is similar to that of a loudspeaker mounted in free air, except that the baffle produces a large increase in \( R_d \) and a small increase in \( L_a \).

It is very important to realize that any baffle or enclosure may be represented in the analogy by a series impedance \( Z_e \) which will tend to reduce the cone velocity, but, depending upon the nature of this additional impedance, partial or complete compensation may be effected by resonant phenomena over at least part of the low-frequency range.

The effective mechanical impedance presented to the cone, due to any acoustical impedance \( Z_m \) is given by: \( Z_m = Z_a (\pi r_e)^2 \)

where \( Z_a \) is the vector sum of \( Z_r \) and the acoustic impedance due to the mounting. At low frequencies

\[
Z_r = R_r + j\omega L_r = \frac{2\nu^2}{c} + j\frac{0.85\nu^2}{\pi r}
\]

**Impedance Curves.**—A very convenient way of measuring the effects of the enclosure on the output of the loudspeaker, is to plot the impedance/frequency curve of the loudspeaker, when housed in the enclosure. If a base line is drawn at a value equal to the clamped impedance of the voice coil, then the impedance curve relative to this line is directly proportional to the velocity of the cone.

The relationships between the electrical impedance \( (Z_e) \) the mechanical impedance \( (Z_m) \) and the velocity \( (v) \) of a loudspeaker system, are as follows: where \( B = \) flux density in the magnet system, \( l = \) length of voice coil conductor enveloped by flux, \( i = \) current flowing in coil.

Back e.m.f. due to the motion of the coil:

\[
E = B i v = \frac{B l i v}{Z_m}
\]

Motional impedance of the coil:

\[
Z_m = \frac{E}{i} = \frac{B l v}{Z_m}
\]

Total electrical impedance:

\[
Z_e = Z_m + Z_m
\]

where \( Z_m \) is the clamped impedance of the voice coil.

From above \( v \propto \frac{1}{Z_m} \propto Z_m \)

If the component parts of \( Z_m \) are expressed in c.g.s.

\[
c = \text{velocity of sound in air.}\]
\[
C_o = \text{compliance of air in closed cabinet.}\]
\[
C_i = \text{compliance of cone suspension.}\]
\[
F = \text{force applied to cone.}\]
\[
k = \omega / c = \text{wave constant.}\]
\[
L_a = \text{length of coil.}\]
\[
L_e = \text{acoustic radiation mass.}\]
\[
M_e = \text{mass of cone system.}\]
\[
M_v = \text{mass of air in vent.}\]
\[
P = \text{radiated acoustical power.}\]

**SYMBOLS**

\[
X_o = \text{reactance of air in closed cabinet.}\]
\[
X_m = \text{total mechanical reactance.}\]
\[
Z_a = \text{total acoustic impedance.}\]
\[
Z_e = \text{acoustic radiation impedance.}\]
\[
Z_m = \text{impedance due to loudspeaker mounting.}\]
\[
X_m = \text{motional impedance of coil.}\]
\[
\nu = \text{velocity of cone.}\]
\[
\omega = 2\pi f.\]

C.g.s. units for mechanical and acoustical quantities, and e.m. units for electrical, have been assumed throughout.

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**Wall Mounting.**—The nearest practicable approach to the infinite baffle condition is by mounting the loudspeaker in a wall e.g. a partition wall between two rooms.

This method of baffling a loudspeaker ensures complete separation between the front and rear radiation of the cone and imposes a relatively low mechanical impedance to the cone velocity. The extent of the low-frequency response is limited by the resonant frequency of the cone.

For wall mounting it is therefore desirable to use a loudspeaker having a low-frequency, highly-damped cone resonance. The damping in this case will be mainly electromagnetic, i.e. a high value of \( R_d \) in the analogy, tending to produce constant velocity conditions and resulting in a falling low-frequency response, as we have shown. Since under these conditions the cone displacement at resonance does not exceed the level required to maintain the velocity constant, a considerable amount of bass lift may be applied from the amplifier to compensate for this loss at low frequencies. The bass lift required commences at the frequency at which the wavelength is equal to twice the cone diameter, and has a slope which may be determined either aurally, or from the expressions previously given, the latter being possible only when the necessary loudspeaker parameters are known.
A consideration which should be borne in mind, particularly in the case of wall mounting, is that the aperture in which the loudspeaker is mounted will behave as a tube of length equal to the thickness of the wall or baffle, and in so doing will exhibit a number of harmonically related resonances and anti-resonances, causing irregularities in the treble response. There are, of course, a number of obvious remedies for this, e.g. bevelling the edges of the aperture or mounting the loudspeaker on a sub-baffle.

Finite Baffles.—If the baffle is finite, at some low frequencies, depending on its size, back-to-front cancellation will occur, and the limiting baffle size for a given low-frequency extension is:

\[ l = \frac{c}{2f} \]

if the baffle is rectangular and \( l \) is the length of the smallest side.

If the bass response is to extend down to a reasonably low frequency, the necessary baffle size will be relatively large, e.g. a square baffle suitable for reproduction down to 60 c/s will have a side of 9.42ft. A loudspeaker acting as a treble unit in a crossover system should be mounted on a baffle large enough to work down to half the crossover frequency.

For the sake of convenience, baffles often take the form of open-backed cabinets. In such cases, in addition to the normal baffle action, the cabinet will behave, more or less, according to its depth, as a tuned pipe, and will exhibit a number of harmonically related resonances, the lowest of which will approximate to:

\[ f = \frac{c}{2(l + 0.85r)} \]

where \( l \) is the depth of the cabinet, \( r = \frac{\sqrt{A}}{\pi} \) if \( A \) is the area of the open back.

It is these resonances that contribute to the unnatural "boomy" quality evident in many commercial reproducers.

Closed Cabinets.—Alternatively a method of preventing back-to-front cancellation, is to completely enclose the rear of the loudspeaker cone. Under these conditions, however, the enclosed air will apply a stiffness force to the rear face of the cone.

This may be represented by a mechanical reactance \( X_{cb} \) the value of which is given by:

\[ X_{cb} = \frac{pc^2 \left( \frac{\pi r^2}{4} \right)^2}{\omega V} \]

where \( \frac{\pi r^2}{4} \) = piston area of cone and \( V \) = volume of enclosure.

In the analogy, this reactance appears as a series capacitance as shown in Fig. 2.

In order not to raise the cone resonance unduly, the value of \( C_b \) must be large relative to \( C_c \). Since, for a given loudspeaker system, \( C_b \) is the only variable, it must be large.

It has been found that, for a 12-in loudspeaker having a fundamental cone resonance at 35 c/s, the volume of an enclosing box would need to be of the order of 12 cu ft for its reactance to be sufficiently low not to impair the low-frequency performance of the speaker.

There are a number of factors in the design of loudspeaker enclosures which should be considered.

These are common to most types of enclosure and are:

Shape of the Enclosure.—As the frequency is lowered the radiated wavefront from the loudspeaker cone tends to become spherical, consequently the boundary edges of the loudspeaker enclosure constitute obstacles in the path of the wavefront. This results in (a) bending of the wavefront (diffraction), and (b) secondary radiation from these edges. This secondary radiation will produce interference patterns, causing irregularities in the frequency response of the system.

These effects are largely dependent on the shape of the enclosure, and will be smallest for a spherical enclosure, and greatest for a cube. Since the cabinet has to be a presentable piece of furniture, there are certain limitations on its shape. Fortunately, however, the effects of diffraction are not very serious, and it is not difficult to reach a compromise.

Corner Position.—Consider a source of sound that is small compared to a wavelength and situated in free space. The radiation from this source will be of equal intensity at a given distance in all directions, i.e. spherical.

If a large flat wall is placed near the sound source, then the total radiation will be concentrated into a hemisphere, and its intensity will then be doubled. Similarly, if a second wall is placed near the sound source at right angles to the first, the total radiation will be concentrated into one-quarter of a sphere and its intensity will be four times greater. A third wall at right angles to the other two will increase the intensity eight times.

A loudspeaker standing in the corner or the room may, at medium low frequencies, be regarded as similar to the second case, and approaching the third case as the frequency calls to a point where the wavelength is much greater than the height of the speaker above the floor.

Construction.—At frequencies where the wavelength is comparable to the internal dimensions of the enclosure, reflections between inside wall facets will occur, resulting in standing-wave patterns, which in turn will produce irregularities in the frequency response of the system.
These standing waves may be considerably reduced (a) by lining the enclosure walls with soft felt or wool thus providing absorption at points of maximum pressure, (b) by hanging curtains of the same material near the centre of the enclosure, thereby introducing resistance at points of maximum velocity.

A further point to be considered is that the material (usually wood) from which the enclosure is made, possessing both mass and compliance, will be capable of movement and will resonate at one or more frequencies and, in so doing, will (a) behave as a radiating diaphragm and (b) modify the air loading on the cone, both of which will produce unwanted coloration in the reproduction. The enclosure should, therefore, be made of as thick and dense a material as possible.

Vented Enclosures, Reflex Cabinets.—One method of overcoming the disadvantage of the closed cabinet, to include in the cabinet wall an orifice or vent.

An enclosure, suitably vented, will apply to the rear of the loudspeaker cone an impedance which offers the cone a maximum degree of damping at, or near, its resonant frequency and the radiation from the rear of the cone becomes much higher at this frequency than at any other. This system will have a resonant frequency at which the mass of air in the duct will "move most readily, bouncing, as it were, on the elasticity of the air in the enclosure. This occurs when the sum of the reactances, which are opposite in sign, is zero.

Equating the two expressions and transposing for \( f \), we have

\[
f = \frac{c}{2\pi} \sqrt{\frac{\pi r^2}{Vl'}}
\]

which is the usual expression for the natural frequency of a Helmholtz resonator.

In actual fact, this is only an approximation, since the full expression for the mass reactance should contain a Bessel term for the load on the vent, due to the air outside the cabinet, but in practice this is small enough to be neglected.

Some of the air adjacent to the end of the duct moves with the air in the duct, and thus becomes added to it. The effective length of the duct, therefore, is greater than its actual length. Rayleigh shows that the increase at each end is:

\[
\delta l = \frac{8}{3\pi} r_v
\]

where \( r \) is the radius of the duct.

The total effective length is, therefore:

\[
l' = l + \frac{16}{3\pi} r_v = l + 1.7r_v
\]

If the duct is not circular, \( r_v = \sqrt{A/\pi} \), where \( A \) is the cross-sectional area of the duct.

Returning now to the subject of loudspeaker enclosures, a vented cabinet containing a loudspeaker will exhibit a resonance in accordance with the above description, which will be reasonably independent of the loudspeaker cone resonance.

When the cabinet resonance is excited by the loudspeaker, the motion of the air in the vent will reach its maximum velocity and will be in phase with the motion of the cone. At this frequency, therefore, the air in the cabinet will come under the double compressive and rarefactive forces of both the cone and air in the vent; consequently, its effective stiffness rises, and the resulting impedance applied to the rear of the cone becomes much higher at this frequency than at any other.

If the resonant frequency of the enclosure is made to coincide with that of the cone, the latter receives maximum damping at its resonance and any peak in the radiated power at this frequency is removed.

In addition to this, the reduction in cone displacement results in a considerable increase in the power-handling capacity of the loudspeaker and
in a reduction of harmonic and intermodulation distortion. Although the velocity and therefore the power radiated from the cone is reduced around this frequency, the overall radiated power from the system is increased considerably, due to the very high air velocity at the vent. Unlike the cone there is no physical limitation to the displacement of the air in the vent.

Below the resonant frequency of the enclosure the stiffness reactance becomes high, and the system behaves as though the air mass in the vent were coupled directly to the mass of the cone. At some frequency the reactance of this combined mass will become equal to the stiffness reactance of the suspension system of the cone. A resonance will occur at this frequency, the amplitude of which will be considerably lower than that of the initial cone resonance, and the radiation from the vent will be in anti-phase with that from the cone.

Above the resonant frequency of the enclosure the mass reactance of the vent becomes high, and the cabinet behaves as though it were completely closed, presenting a purely stiffness reactance to the rear of the cone. At some frequency the combined stiffness reactance of the cone suspension system and the enclosure will become equal to the mass reactance of the cone. At this frequency a further resonance will occur, and again the amplitude will be considerably less than the cone resonance.

Now let us consider the nature of the impedance presented to the rear of the cone by a vented enclosure. Since this impedance rises to a maximum value, a parallel tuned circuit is indicated in the analogy Fig. 3, where $R_v$ and $M_v$ are the vent components.

By drawing the reactance sketches for the complete system, we are able to see clearly the derivation of

![Image](image-url)

**Fig. 5. Impedance/frequency response of a loudspeaker on an infinite baffle and in a vented enclosure.**

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One method of applying these properties to loudspeaker mounting, is to use an open pipe with the loudspeaker mounted at one end, the length of the pipe being such that its fundamental anti-resonance coincides with the cone resonance thus securing some of the advantages of a reflex enclosure.

A closed pipe may also be used in the same manner, in which case the length of the pipe need only be about half that of the open pipe. However, the impedance presented to the cone by this method is high, and a serious reduction in cone velocity may result at low frequencies. The radiation from the open end of the open pipe increases the radiation efficiency of this system to some extent.

The length of an open pipe for a given frequency of anti-resonance \( f \) is:

\[
l = \frac{c}{2f} - 1.7 \sqrt{\frac{A}{\pi}}
\]

where \( A \) is the cross-sectional area of the pipe.

The length of a closed pipe for a given anti-resonance frequency \( f \) is:

\[
l = \frac{c}{4f} - 0.85 \sqrt{\frac{A}{\pi}}
\]

Whilst these pipes are a little more simple to construct than reflex enclosures, their overriding disadvantage is the presence of all resonances and anti-resonances occurring at every quarter wave length, and it is virtually impossible to damp the enclosure and to absorb all the resonances without severely attenuating the required fundamental. A way of partially overcoming this is described in a patent by Voigt. This is to mount the speaker in the wall of a pipe which is closed at one end and open at the other, the position of the loudspeaker being \( \frac{1}{3} \)rd of the pipe length away from the closed end. By this means, the first resonance above the fundamental (3rd harmonic) will be cancelled.

The Labyrinth.—The labyrinth consists of a very long tube, usually folded and heavily lined with absorbing material, with the loudspeaker mounted at one end. The labyrinth is probably the cleanest way of disposing of unwanted back radiation, which, having left the rear of the loudspeaker cone at one end of the tube does not reappear at the other. It does not really matter therefore, whether this far end is open or closed.

The analogous circuit is that of a transmission line and is shown in Fig. 6. The sound energy, due to the back radiation from the cone, is largely dissipated in the resistive components \( R_1 \) and \( R_2 \), where \( R_1 \) is due to the viscous losses between the air in motion and the lining on the internal surfaces of the labyrinth, and \( R_2 \) is due to the absorption of sound energy at these surfaces.

As the frequency is increased, \( R_1 \) increases and \( R_2 \) decreases. Therefore, if the labyrinth is to be effective at the lower frequencies, the lining must be fairly thick. If, however, this begins to take...
up an appreciable part of the cross-sectional area of the labyrinth, the air loading on the rear of the cone, which is normally quite high in this type of enclosure, will become excessive, resulting in a severe reduction in the radiated power at these frequencies. The cross-sectional area should, therefore, be at least equal to the piston area of the cone, and, to achieve the necessary dissipation of sound energy from the rear of the cone, the effective path length of the labyrinth should be as great as possible, the minimum length being set empirically at a quarter wavelength equivalent to the lowest frequency to be reproduced.

Under these conditions, the impedance presented to the rear of the cone is quite high and mainly resistive, so that the cone approaches constant-velocity operation and behaves in the manner previously described for this condition.

The Horn.—Horn loading is the most efficient form of loudspeaker mounting and, if the horn were large enough, it would give a performance superior in every respect to any other form of loudspeaker mounting.

The action of the horn can be most readily grasped by consideration of the analogous circuit. The major problem in all the systems so far discussed has been to compensate for the fall in the radiation resistance reflected back to the primary of the transformer at low frequencies. The use of a transformer would be an obvious answer if this problem were an electrical one, and, applying this to the analogy, we have Fig. 7. Acoustically, such a transformer is analogous to the horn, which may be used to match the relatively high mechanical impedance of the loudspeaker cone to the radiation resistance, and, by making the mouth of the horn large, this resistance does not become so low at low frequencies.

From the analogy, since the effective radiation resistance reflected back to the primary of the transformer is very high, the cone operates under constant velocity conditions and no resonance is evident.

Below a certain frequency the acoustic resistance of a horn falls sharply and its reactance (mass) rises. This cut-off frequency is determined by the dimensions of the horn and, since size-for-size an exponential horn maintains its efficiency to a lower frequency than a conical horn, the former is more often used. The cross-sectional area \( A_x \) of the exponential horn at any distance \( x \) from the throat is given by:

\[
A_x = A_0 e^{-m \frac{x}{4}}
\]

where \( A_0 \) is the throat area and \( m \) the flair constant.

The cut-off frequency is given by:

\[
f_c = \frac{mc}{4\pi}
\]

The diameter of the mouth should not be less than a quarter wavelength at \( f_c \), otherwise the horn will tend to exhibit the resonances similar to a tuned pipe.

Most text books on electro-acoustics deal very fully with the horn, and there is little point in our doing so here, especially since, due to its size, an adequately large horn is rarely encountered. Although many small folded horn designs are capable of impressive (if not accurate) reproduction, let it suffice to say that a horn capable of presenting a constant radiation resistance down to 30 c/s to the cone of a 12-in loudspeaker would be over 12ft long and have a mouth diameter of about 9\( \frac{1}{2} \)ft.

Conclusion.—The different types of loudspeaker enclosures number as many as the possible combinations of L C R in series with the analogous cone circuit.

Some time ago, the thought arose that an excellent method of designing a loudspeaker enclosure would be to state the ideal velocity characteristics, and then determine an electrical impedance which, when placed in series with the analogous cone circuit, would produce these characteristics. It would then remain to transpose this impedance into acoustical terms and to evolve an enclosure having the required component values.

This line of development has been followed to a successful conclusion and will be described in the second part of this article.