A loudspeaker system includes a loudspeaker mounted in an enclosure, the enclosure having a front port for exiting the sound energy radiated by the front of the speaker cone and a port, or ports, or other areas for exiting the sound energy radiated by the rear of the speaker cone which is out of phase with the front radiation. The port, ports or areas through which the energy from the back cone surfaces is radiated is made acoustically resistive so as to delay the sound energy in conjunction with the acoustic compliance of the enclosure. The dimensions of the enclosure, the effective resistivity, and the total area from which the speaker rear energy is radiated are chosen so that the sound energy from the rear of the speaker cone effectively cancels out sound arriving from the front of the speaker cone at regions to the rear of the enclosure. This minimizes the effective acoustical energy to the rear of the loudspeaker system so as to make for a forwardly directed sound radiation pattern.

2 Claims, 10 Drawing Figures
DIRECTIONAL LOUDSPEAKER SYSTEM
This invention relates to loudspeaker systems, and more particularly to a loudspeaker combined with an enclosure which provides a directional sound radiation pattern.

In such applications as auditorium speaker systems, public address systems, and loudspeaker systems utilized in telephone conferencing, it is highly desirable to provide sound radiators having directive characteristics with little or no acoustical radiation to the rear thereof. This is in view of the fact that such rearward acoustical radiations often lead to the development of reverberations which seriously interfere with, and reduce the intelligibility of the sound. Further, such rearward radiations often result in feedback to the microphone which sets the system into an oscillatory condition with its discomforting result. While directivity is not too difficult to attain in the high frequency ranges, with horns and the like of modern speaker design, most low frequency speakers, i.e., those which radiate frequencies whose wave lengths are large compared to the enclosure dimensions, have inherently nondirectional characteristics. Most techniques of the prior art for attaining directivity at low frequencies have involved arrays of speakers or single speakers of large radiating area, with the sound energy radiated by the various components of the system being combined with appropriate wave interference patterns to obtain the desired directional properties. These types of systems are very closely frequency dependent for each particular design, and thus it is difficult to attain optimum results over a frequency range wide enough to cover the entire low frequency spectrum of interest for most application requirements (50 to 3,000 Hertz). Such systems of prior art also tend to be somewhat complicated, expensive, and space-consuming.

The system of this invention overcomes the shortcomings of prior art low frequency speaker systems in providing a system utilizing a single speaker housed in a relatively small enclosure which has very low rearward acoustical radiation and a broad forward radiation pattern over the entire low frequency spectrum of interest for most applications. The device of the invention further is of relatively economical and simple design and construction, and occupies a minimum amount of space. Also, the device of the invention is such that it can be adapted for adjustment in the field so as to provide optimum radiation characteristics for the particular application requirements at hand.

It is therefore the principal object of this invention to provide a simple speaker system of relatively compact proportions and economical fabrication which is capable of providing directive acoustical radiation in the low frequency audio range.

It is another object of this invention to minimize the effect of rearward radiation of a low frequency speaker system so as to lessen the poor intelligibility due to reverberation.

It is another object of this invention to minimize the effects of feedback between a speaker and a microphone in a low frequency sound system.

It is still another object of this invention to provide a low frequency speaker system which is capable of easy adjustment in the field for optimum radiation characteristics.

Other objects of this invention will become apparent as the description proceeds in connection with the accompanying drawings, of which:

FIG. 1 is a perspective view of one embodiment of the device of the invention;

FIG. 2 is a perspective view partially cut away showing the opposite side of the embodiment of FIG. 1;

FIGS. 3a and 3b are schematic illustrations illustrating the operation of the device of the invention;

FIG. 4 is a perspective view illustrating a second embodiment of the device of the invention;

FIG. 5 is a perspective view illustrating a third embodiment of the device of the invention;

FIGS. 6 and 6A are perspective views illustrating a fourth embodiment of the device of the invention;

FIG. 7 is a perspective view illustrating a fifth embodiment of the device of the invention; and

FIG. 8 is a perspective view of a sixth embodiment of the device of the invention.

Briefly described, the device of the invention comprises a loudspeaker which is housed in an enclosure, the enclosure having a forward port through which acoustical energy from the forward portion of the speaker cone is exited, and a port, ports, or distributed radiating areas located in the rear or side portions of the enclosure through which acoustical energy radiated by the rear of the speaker cone is exited. The volume of the enclosure, the size of the port, ports, or distributed radiating areas which communicate with the rear of the cone and the resistive action on the sound exiting are all designed so as to make for sound of equal and opposite polarity at azimuths near the rear axis of the speaker enclosure, such components effectively cancelling each other so that most of the acoustic energy is radiated in the forward direction with greatly diminished radiation to the rear. In certain embodiments, the resistive portion of the acoustic impedance is provided by means of resistive material which covers the ports for exiting sound while in another embodiment, the resistance is provided by a plurality of relatively small apertures distributed over the port area. In still another embodiment, the enclosure itself is comprised of a resistive material. Further, in one embodiment, an adjustable cover member is provided for use in setting the rearward acoustical port area in the field. Referring now to FIGS. 1 and 2, one embodiment of the device of the invention is illustrated. Loudspeaker 11 is mounted in speaker enclosure 14 with the front portion 11a of the speaker cone positioned in front aperture 14a. Enclosure 14 has a pair of equal size apertures 14b and 14c formed in the opposite sides thereof. Mounted in 14b and 14c is acoustically resistive material 16 which may, for example, be of fiberglass. Mounted over the pieces of acoustically resistive material 16 to provide a protective covering therefor are thin metallic sheets 18 which have apertures 18a formed therein, the apertures in the protective sheets 18a being sufficiently large so as to be acoustically transparent. Substantially all of the acoustical energy radiated by the front cone portion 11a passes through the front aperture 14a of the speaker enclosure, while the energy components radiated by the rear portion 11b of the speaker cone which are in phase opposition to those radiated by the front portion 11a are exited through side apertures 14b.
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3, 14c, these rear baffle components being phase shifted by resistive material 16 in conjunction with the acoustical reactance of the enclosure volume, and exited substantially equal by the two side apertures.

Referring now to FIGS. 3a and 3b, the operation of the device of the invention will now be explained. Referring particularly to FIG. 3a, the point x is an arbitrarily chosen point at a distance from the speaker which is large compared to the wave length of the sound being considered. \( r_x \) is the distance from the point x to the front of the speaker cone 11a, and \( r_1 \) and \( r_2 \) are the distances from each of the side ports 14a and 14b respectively to the point x. Since the sound exiting from the two side ports 14a and 14b is nearly in phase, they will combine at the remote point x to produce a resultant sound that has phase and amplitude characteristics nearly identical to that which would be produced by a fictitious source on the speaker axis and midway between the ports 14a and 14b. For clarity of explanation, let us additionally refer to FIG. 3b where the acoustic path length between the front of the speaker cone 11a and the rear of the cone and the fictitious sound source \( s \) has been shown schematically. It is to be understood that the selection of the point x in this illustration is quite arbitrary and could have been chosen, for example, to the rear of the enclosure where the resultant sound field would be greatly diminished by virtue of the phase relationships of nearby opposite polarity that exist in that area.

Let us assume the following conditions exist: (1) The distance to the speaker from the remote point x is large compared to the wavelength of the sound being considered; (2) the dimensions of the enclosure are small compared to the wave length of the sound, and (3) the acoustical parameters are properly chosen such that the sound pressure \( P_r \) generated by the motion of the front side of the speaker cone, and the sound pressure \( P_s \) generated by the motion of the rear side of the speaker cone and exited through ports 14a and 14b are equal. Then the sound pressure \( P_r \) at the remote point x may be approximately determined by the following equation:

\[
P_r = \frac{P_s r_1}{r_x} \omega/c [(\phi/c) + \delta_x \cos \theta]
\]

where:
- \( P_s = P_r = P_x \) measured at one meter.
- \( \omega \) is the angular velocity of the sinusoidal signal exciting the loudspeaker.
- \( \theta \) is the angle between the axis of the loudspeaker system (i.e., as represented in FIGS. 3a and 3b by the line A which runs through the center of the speaker baffle and perpendicular thereof) and a line from the center of the speaker to the remote point x.
- \( c \) is the velocity of sound in air
- \( \phi \) is the phase shift in radians imparted to the sound radiated from ports 14a and 14b by the resistive material in conjunction with the reactance of the enclosure volume.
- \( \delta_x \) is the effective acoustic path length from the front side of the speaker cone to the apparent point of radiation of the sound being exited by the near ports 14a and 14b, i.e., a point on the axis of the loudspeaker system.

\( r \) is the distance from the center of the system to the remote point, i.e., in common vector notation

\[
r = \left( \sqrt{r_1^2 + r_x} \right) / 4
\]

If the phase shift \( \phi \) is made proportional to frequency i.e., a time delay is introduced, the directional characteristics of the system will be independent of frequency for the specified conditions. This end result can be achieved by subjecting the sound emanating from the rear side of the speaker cone to a time delay of \( \tau \) seconds. Substituting \( \sigma \) for its equivalent \( \phi \) in equation (1) results in the following equation:

\[
P_r = \frac{P_s r_1}{r_x} \omega/c (c \tau + \delta_x \cos \theta)
\]

Equation (2) belongs to a family of curves called limacons of the form \( a + b \cos \theta \) with \( a = c \tau \) and \( b = \delta_x \). The cases where \( a = b \) and \( a = b/3 \) are of special interest and result in directional patterns which are known as the cardiodi and hyper-cardiodi respectively.

The desired delay \( \tau \) is achieved in this device by means of subjecting the sound emanating from the rear side of the speaker cone to an acoustical compliance in conjunction with an acoustical resistance. This time delay at low frequencies is numerically equal to the product of the acoustical compliance and resistance. When expressed as an equation, this delay is given as:

\[
\tau = \text{Resistance} \times \text{Compliance} = \frac{RV}{r \omega^2 A}
\]

This relationship can be rearranged to give the exit port area, \( A \), needed for a given enclosure volume and acoustic resistance material to produce a particularly desired radiation pattern

\[
A = \frac{RV}{r \omega^2} \tau
\]

Where:
- \( R \) is the specific acoustic resistance of the resistance material used in M.K.S. rays,
- \( V \) is the volume of the enclosure in meters\(^3\),
- \( \rho \) is the density of air,
- \( c \) is the speed of sound and air, and
- \( \tau \) is the time delay to which the sound radiation from the side ports is subject in seconds.

As an example, let us assume that a hyper cardiod pattern is desired and the following parameters are to be used:

- Enclosure dimensions = 18” \( \times \) 18” \( \times \) 10”
- \( R = 100 \) M.K.S. rays

As already noted in connection with equation (3) above for a hyper cardiodi, \( a = b/3 \). Thus, for this particular design, by solving equation (3) we find that \( \tau = \Delta x/3c \), and with the particular given parameters, \( \tau \) is 2.98 \( \times 10^{-4} \) sec. Solving equation (5) then for \( A \) gives 7.9 \( \times 10^{-2} \) M\(^2\), or approximately a total port area of 50 sq. inches. This may be divided between two ports as in the embodiment already described, or may be incorporated into a single port for the embodiment to be described in connection with FIG. 4.

Thus, in implementing a practical design, the acoustical signals arriving at a remote point x which originate from the near rear portions of the speaker cone (as shown in FIG 3b) are nearly 180° out of phase with those arriving from the front portion of the speaker cone (illustrated in FIG 3a). These signals thus effectively cancel each other out so that there is reduced radiation at this point. The design thus is implemented to cancel out radiation rearward of the
speaker by virtue of the control of the phasal relationships between the signals arriving in these areas. The radiation to the frontward of the speaker, on the other hand, has a fairly broad radiation pattern.

Referring now to FIG 4, another embodiment of the device of the invention is illustrated. In this embodiment, rather than having two symmetrically arranged side ports for exiting the energy from the rear portions of the speaker cone, a single exit port 14b is utilized, this single port having the total area necessary to achieve the desired radiation pattern. Port 14b, as for the ports of the first embodiment, is covered with acoustical material 16 having an acoustically transparent covering 18, which may be fabricated of sheet metal having apertures 18a formed therein. The embodiment of FIG. 4 is designed and operates in the same manner as described for the embodiment of FIGS 1 and 2, the only difference being that all of the acoustical port area is provided in the single port rather than being divided as in the previous embodiment.

Referring now to FIG 5, a further embodiment of the device of the invention is illustrated. In this embodiment, rather than utilizing a single aperture which is covered with acoustical material, the acoustical resistance is achieved by making a plurality of relatively small apertures 14d in the rear wall of the speaker enclosure 14.

As is well known in the art, such an apertured surface in a speaker enclosure provides an acoustical resistance which is dependent upon the size of the apertures. Thus, a port for the acoustical energy radiated by the rear portions of the speaker cone can be provided with a desired time delay in the same manner as described in connection with the previous embodiments.

Referring now to FIGS. 6 and 6a, an embodiment of the device of the invention in which the effective size of the rear exit port can be experimentally adjusted in the field is illustrated. In this embodiment, a single round port 14b is provided in the back wall of speaker enclosure 14. Completely covering port 14b, as for the previous embodiments, is acoustically resistant material 16 which has a perforated metal sheet 18, adhered thereto, to protect it from damage, sheet 18 being acoustically transparent.

Held to the back wall of enclosure 14 by means of adjustable wing nut 25 is circular adjustable baffle member 27. Baffle 27, as can be seen in FIG. 6a, is formed from a steel plate 28 which is thick enough to be acoustically opaque (about one-eighth inch) which has adhered to its surface a felt lining 30. Baffle member 27 may be selectively positioned so as to expose all or any portion of exit port 14b, the baffle being held in any desired position by tightening wing nut 25 with felt liner 30 abutting tightly against the back wall of the enclosure. Thus the effective size of exit port 14b can be adjusted in the field experimentally for an optimum acoustical radiation pattern.

It is to be noted that the exit ports for the rearward acoustical energy could also be located in the top or bottom portions of the speaker enclosure, provided of course that these portions are exposed and that the needed area for these ports is available. Variations of the value of the acoustical resistance may also be made in a further embodiment by causing the resistive material to be compressed between acoustically transparent sheets of perforated metal.

Referring now to FIG. 7, a further embodiment of the device of the invention is illustrated. In this embodiment, side top and back portions 32-34 are fabricated of an acoustically resistive material which is attached to a supporting frame 37. Thus, the volume of the enclosure is defined by the resistive material. In this embodiment, the thickness of the resistive material is experimentally changed, i.e., successive layers added, until the desired radiation pattern is achieved. This is necessary since the sound exiting area is essentially equal to that of the sides made from the resistive material and is not easily adjustable. The speaker 11 is mounted in front baffle 43.

Referring now to FIG. 8, another embodiment of the invention is shown. In this embodiment, strips 35 of acoustically resistant and resilient material such as a plastic foam are placed between the back cover 36 of the enclosure and back posts 38 of the enclosure frame to form acoustical ports 39 and 40. The acoustical resistance of the ports can then be adjusted by tightening or loosening screws 42 so as to vary the degree of compression of strips 35 and thus changing both the effective areas of the ports and the characteristics of the resistive material.

The device of this invention thus provides simple yet highly effective means for controlling the radiation pattern of a low frequency speaker system so as to minimize radiation to the rear of the speaker which causes undesirable distortion.

While the device of the invention has been described and illustrated in detail, it is to be clearly understood that this is intended by way of example and illustration only and is not to be taken by way of limitation, the spirit and scope of this invention being limited only by the terms of the following claims.

I claim:

1. A speaker system comprising:
   a speaker member having a cone with front and rear portions for radiating acoustical energy in phase opposition relationship and an enclosure in which said speaker is mounted, said enclosure having a port formed therein for exiting the acoustical energy radiated by the front portions of said cone to the front of said enclosure, the improvement comprising:
   a pair of similar ports formed in the sides of said enclosure for exiting a predetermined amount of energy radiated by the rear portion of said cone, and
   resistive material for providing a predetermined acoustical resistance covering said ports so as to time delay the acoustical energy exited from said ports,
   said ports having a predetermined area, said enclosure having a predetermined volume, and said resistive means providing a predetermined acoustical resistance such that the acoustical energy exiting from said ports within a predetermined frequency range effectively reduces the acoustical energy radiated by the front portions of said cone within said frequency range at substantially all points to the rear of said speaker enclosure.
2. The device of claim 1 wherein the acoustical radiation pattern of said speaker system within a predetermined frequency range is a hypercardioid and the total effective area, $A$, of said port means is in accordance with the following equation:

$$A = \frac{RV}{\rho c^2 \tau}$$

where:

$R$ is the specific acoustic resistance of the exit port material,
$V$ is the volume of the enclosure,
$\rho$ is the density of air,
$c$ is the velocity of sound and air, and
$\tau = \Delta x/3c$, where $\Delta x$ is the effective acoustical path length from the front side of the speaker cone to the apparent point of radiation of the sound exited by the port means.

* * * * *