Oct. 16, 1956 J. J. BARUCH ET AL 2,766,839

LOUDSPEAKER SYSTEM

Filed March 16, 1953 2 Sheets-Sheet 1

Fig. 1

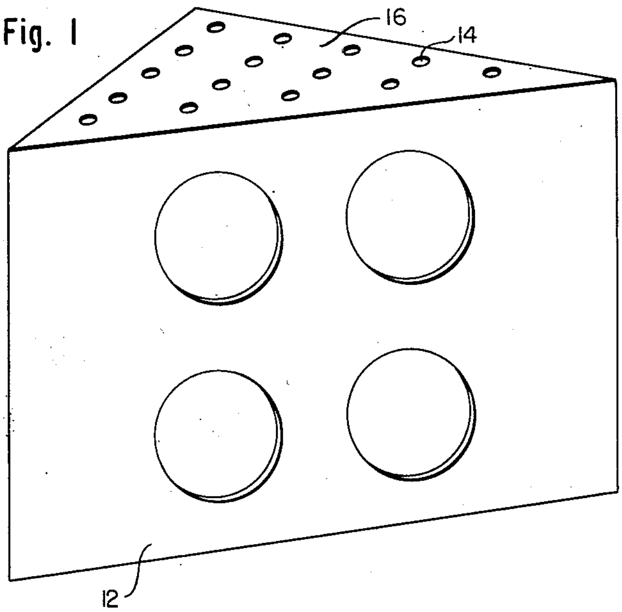


Fig. 2

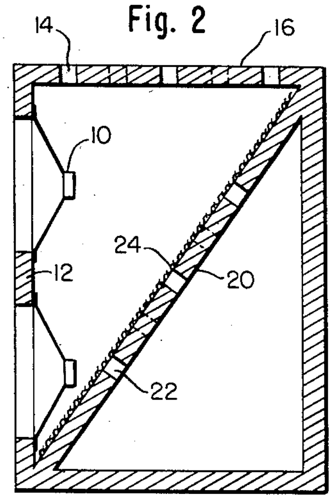
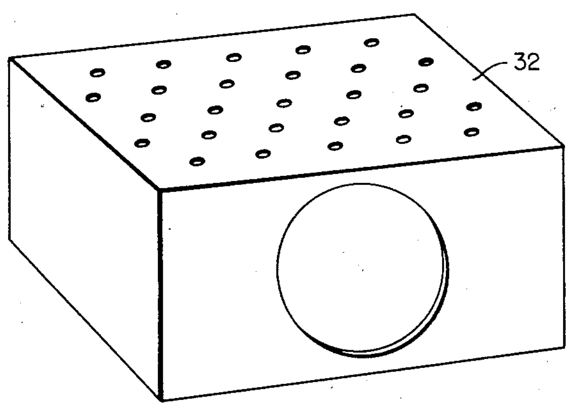


Fig. 3



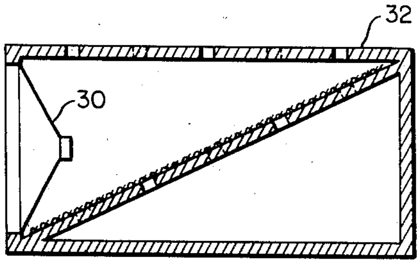


Fig. 4

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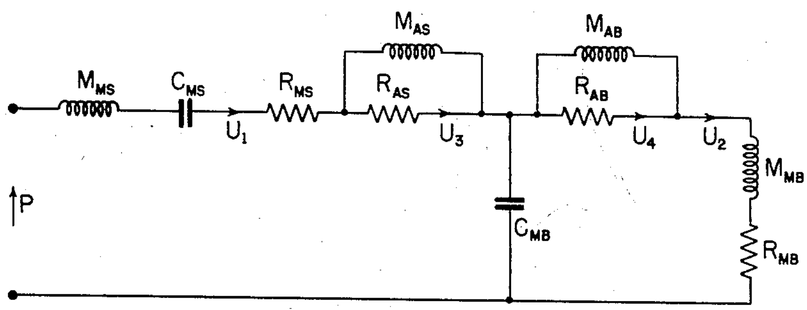

Fig. 5

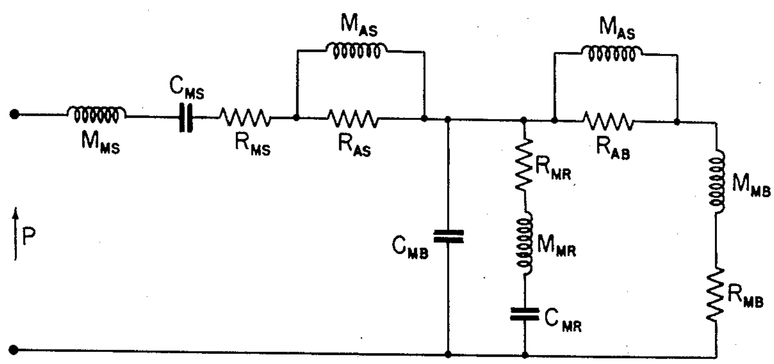

Fig. 6

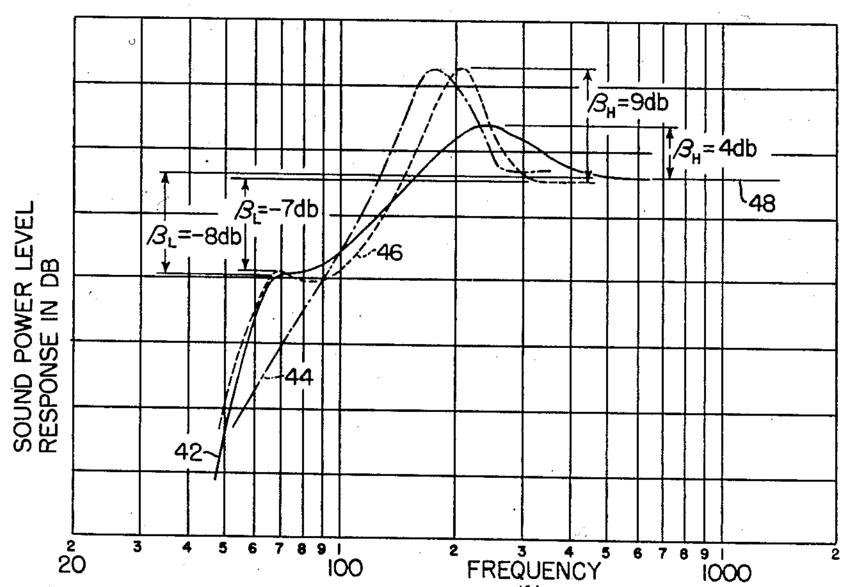

Fig. 7

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LOUDSPEAKER SYSTEM

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Application March 16, 1953, Serial No. 342,554

3 Claims. (Cl. 181—31)

The present invention relates to loudspeaker systems, and is concerned primarily with the provision of loudspeaker systems of simple and compact construction which permit a wide frequency response to be obtained from relatively low cost speaker driving units. More specifically, the invention is directed to speaker enclosures of novel construction and arrangement which, when suitably correlated with the parameters of the driving units, permit a substantial reduction in cabinet size as compared with conventional designs while providing a wide frequency response.

The problem of obtaining adequate bass response in radio equipment and other forms of sound reproducing apparatus has received the attention of many investigators. Because of the decrease in effective coupling between the usual loudspeaker cone diaphragm and the air mass as the frequency is lowered, the bass response generally falls at a rate of 12 to 18 db per octave, beginning at a frequency corresponding approximately to the resonant frequency of the speaker in free air. Thus, a loudspeaker mounted in a wall or in a large box so that one side only of the speaker cone may radiate to the listener, shows a drop of 12 db per octave, while a speaker mounted in an open back enclosure, on a small baffle, or in a ported or vented type enclosure will show an 18 db fall-off per octave.

Because of the requirement that the so-called total enclosure or closed box type have a very considerable volume if the resonant frequency of the speaker is not to be unduly raised by the stiffness of the enclosed volume at the rear of the speaker, the ported or vented form of enclosure has been extensively employed. The usual type of such enclosure is one which consists of a simple box having, adjacent the speaker opening, a single port communicating between the inside and the outside of the box. The port introduces a mass which resonates with the box compliance, the box volume and port size being selected to cause the resonance to occur in the vicinity of the speaker resonant frequency. As a result, a response curve of the system shows a double peak, with a relatively high peak, compared to speaker mid-range output, occurring somewhat above the original resonant frequency of the speaker and another peak, of lesser magnitude than the mid-range plateau, occurring below speaker resonance. The separation of the peaks above and below the tuned frequency of the enclosure is a function of box volume, the peak separation increasing with decrease in enclosure volume.

While it might appear that the response below speaker resonance might be somewhat improved, as compared with infinite baffle or total enclosure response, by moving the lower peak downwardly through use of a small volume enclosure, it has been recognized that this leads to generally unsatisfactory results, since the upper peak is correspondingly increased in frequency and also undergoes a substantial increase in amplitude, so as to introduce a very noticeable and highly objectionable resonance. A further objection to increasing the separa-

tion of the peaks is that the lower peak becomes relatively less significant, since the port size, and therefore its radiation effectiveness, must be made smaller as the box volume is decreased, in order that the box may still be tuned to the speaker resonant frequency.

It has therefore been the practice, in vented enclosures, to employ enclosures having a volume generally in excess of five or six cubic feet to provide a relatively small peak separation, and to employ driving units that have a fairly low resonant frequency. Even in cases where large driving units having heavy magnet structure and highly compliant, large diameter cones are employed, the bass response below speaker resonance is generally unsatisfactory since the port area is inadequate to provide appreciable radiation in the frequency range from speaker resonance down to the lower peak, while below this peak the phase relation betwen the radiation from the front of the cone and from the port is such as to give rise to substantial cancellation, accounting for the 18 db per octave fall-off that is characteristic of speaker systems of this type.

With a view to providing a satisfactory wide range response characteristic in a relatively low cost unit that may be small in size compared to conventional enclosures, the present invention has as an object the provision of loudspeaker systems employing enclosures of novel construction and embodying novel principles, wherein appreciable radiation may be caused to take place at frequencies well below the normal resonant frequency of the driving unit or units.

More specifically, it is an object of the invention to provide a loudspeaker system wherein relatively small loudspeaker units may be utilized, such units being sufficiently small and lightweight to serve as effective radiators of high frequencies, thereby permitting the same unit or units to serve both as the low frequency and high frequency radiating elements with consequent saving in cost.

Still another object of the invention is the provision of a loudspeaker system wherein the resonant peaks that are characteristic of a ported or vented enclosure may be widely spaced above and below the nominal resonant frequency of the speaker without involving an excessive and objectionable upper resonance peak and without depressing unduly the lower peak. More specifically, the invention contemplates a novel form of porting means for communication between the interior and the exterior of the enclosure whereby enhanced low frequency radiation from the port means may be obtained, in part through control of the phase relations and coupling characteristics between the port region and the front of the cone, in the desired frequency range.

To this end, the invention has as a feature a loudspeaker system of relatively small enclosed volume so as to provide a substantial separation of the resonance peaks, the system embodying means within the enclosure to minimize the upper resonance peak, and porting means comprising a plurality of spaced apertures to provide an enhanced response in the region of the lower resonance peak. The plurality of small spaced apertures makes it possible to provide, in both the porting means and in the internal means for controlling the upper resonance peak, appropriate mass and resistance values for the proper operation of the system, and in the case of the port or vent, an enhanced radiation of the lower frequencies as compared with conventional single port construction.

In the drawings illustrating the invention in its several embodiments and its theoretical aspects,

Fig. 1 is a front oblique view of one form of loudspeaker system embodying the invention.

Fig. 2 is a vertical sectional elevation thereof.

Fig. 3 is an oblique view of an alternative embodiment of the invention.

Fig. 4 is a vertical sectional view thereof.

Fig. 5 is a representative equivalent circuit diagram of a loudspeaker system employing a loudspeaker mounted in a vented enclosure.

Fig. 6 is a representative equivalent circuit diagram of a loudspeaker system including additional internal means for the control of the upper resonance peak.

Fig. 7 is a plot of curves illustrating the improved low frequency performance of a typical loudspeaker system embodying the invention, in comparison with systems of the same size but not utilizing the features of the invention.

As has been indicated, the invention is primarily concerned with providing a loudspeaker system characterized by exceptionally small box volume yet with satisfactory low frequency response even where relatively small speaker units are employed that do not possess a particularly low resonance frequency. As a result, a system having acceptably wide frequency response may be provided at low cost, since the same driving unit or units may also be made to provide appreciable response in the region of 10 kc./s. and above, if desired.

The embodiment shown in Figs. 1 and 2 makes use of a plurality of small loudspeaker units 10 arranged on the front wall 12 of a generally triangular enclosure of small dimensions. By way of example, a representative system may employ an enclosure having a volume of only about one-half cubic foot. The structure must be rigidly constructed, with adequate wall thickness to resist vibration under the considerable pressures generated during operation. The porting or venting of the enclosure is provided by a plurality of spaced apertures 14 in the triangular top wall 16. The diameter and depth of these apertures are determined by suitable calculations based on the characteristics of the speaker units and the volume of the enclosure, as hereinafter fully set forth and described.

By reason of the fact that the speaker system will preferably be utilized by mounting in a corner of a room or, still better in the intersection of walls and floor or ceiling, the ported top wall 16 of the enclosure (or bottom, if the speaker is inverted for mounting adjacent ceiling level) will be normal to two extended surfaces of the room. This serves to enhance the effectiveness of the low frequency radiation from the ported area of the speaker system.

The speaker system likewise embodies an internal ported member comprising an inclined partition 20 having spaced apertures 22 providing communication between the two chambers into which the enclosure is divided. Damping means 24 in the form of thin fibrous material or of other suitable composition is employed in association with the apertured partition to control the acoustic transmission therethrough. The purpose of this internal partition is to minimize the amplitude of the upper resonance peak so as to permit the use of a small volume enclosure in the desired manner.

An alternative embodiment of the invention is illustrated in Figs. 3 and 4, wherein a single loudspeaker unit, for example a single 10″ or 12″ unit, may be employed in a small volume enclosure. In this embodiment, of rectangular configuration, the speaker 30 is mounted on one of the smaller walls in order that the ported area may utilize a relatively large wall 32, while still permitting the enclosure volume to remain small, generally less than two cubic feet.

It is to be understood that the illustrated embodiments are merely representative of possible constructions utilizing the principles of the invention, and that other forms and arrangements may be employed, constructed in accordance with the novel design principles of the invention and providing the improved response characteristics afforded thereby.

The effective utilization of the invention to provide the desired response requires that the characteristics of the enclosure, and particularly the porting, be properly correlated with the loudspeaker unit or units. While some degree of correlation of these factors has been recognized as desirable in conventional ported enclosures, the utilization in the present invention of novel elements in the system and the extension of the performance into regions beyond that heretofore attemped makes it desirable to carry out the correlation of speaker and enclosure characteristics to a greater degree than has generally been done heretofore.

For an understanding of the design principles involved and the mode of operation of the invention, the system will first be described in terms of the equivalent electrical circuit of Fig. 5 which represents a loudspeaker mounted in a ported enclosure. In this equivalent circuit, current U is analogous to volume velocity in cm.^{3}/sec., while voltage P is analogous to pressure, in dynes/cm.^{2}. The symbols are defined as follows:

M_{MS} represents the mass associated with the coil assembly and cone assembly of the loudspeaker (in gms./cm.^{4})

C_{MS} represents the compliance of the speaker (in cm.^{4} sec.^{2}/gm.)

R_{MS} represents the mechanical dissipation in the speaker system (in gms./cm.^{4} sec.)

M_{AS} represents the mass of the air load on the speaker (same units as M_{MS})

R_{AS} represents the mechanical dissipation involved in the air load (same units as R_{MS})

M_{MB}, C_{MB} and R_{MB} represent respectively the mass, compliance and dissipation of the enclosure

M_{AB} and R_{AB} represent respectively the mass and dissipation (or radiation resistance) associated with the port in the enclosure.

In providing a system embodying the invention, it is first necessary to determine the speaker characteristics, namely, the parameters M_{MS}, C_{MS}, R_{MS}, R_{AS} and M_{AS}. These are derived by a combination of measurement and calculation, as hereinafter illustrated by typical examples. From the speaker characteristics, the enclosure parameters C_{MB} and M_{MB} may be determined to properly match the speaker unit or units, while providing the desired substantial separation of the peaks. The box compliance C_{MB} defines the box volume required, while the box mass (provided by the inductance of the port) provides one of the parameters influencing the port design.

In general, R_{AS} and M_{AS} will be derived by calculation, while M_{MS}, C_{MS} and R_{MS} are determined from a frequency response curve and measurement of either the compliance of the speaker suspension, or of the mass of the coil and cone assembly. A frequency run of the speaker in an infinite baffle will reveal the resonant frequency ω_n and the Q. For a speaker having an effective piston area S_D in cm.^{2}, the resistive component of the air load, R_{AS}, is given by

$$R_{AS}=\frac{1.4\rho c}{S_D} \text{ in gms./cm.}^4\text{ sec.}$$

and M_{AS}, the air mass load on one side of the speaker cone, by

$$M_{AS}=R_{AS}\frac{d}{3c} \text{ in gms./cm.}^4$$

where

ρ=density of air=1.2 kg./m.^{3}

and

c=speed of sound=344 m./sec.

(both at normal atmospheric conditions)

and

d=effective piston diam in cm.

Assuming that the mass of the coil and cone assembly has been obtained, then

$$M_{MS}=\frac{\text{mass of coil and cone assembly}}{S_D{}^2}$$

The compliance C_{MS} of the speaker may then be found by substituting the values for ω_N, M_{AS} and M_{MS} in the expression (assuming purely reactive impedances at the frequencies involved)

$$\omega_N^2=\frac{1}{(M_{MS}+2M_{AS})C_{MS}}$$

Note that in this equation, the value of M_{AS} must be doubled, since the speaker compliance C_{MS} is being determined on the basis of speaker characteristics in an infinite baffle, where there is an air load on both sides of the cone.

The value of R_{MS} may be calculated from the speaker Q or may be obtained by measurement of the speaker characteristics in an exacuated chamber to eliminate the air load.

In correlating the enclosure with the speaker unit or units, the enclosure is preferably tuned to the resonant frequency of the speaker when mounted in the enclosure. This resonant frequency ω_0 will be higher than the infinite baffle resonant frequency ω_N, due to elimination of the back mass load on the speaker cone.

The resonant frequency ω_0 of the system is given by

$$\frac{1}{\omega_0^2}=C_{MS}M_{TS}$$

for the case of relatively small enclosures such as employed in the present invention.

For the tuned condition,

$$C_{MS}(M_{MS}+M_{AS})=C_{MB}(M_{MB}+M_{AB})$$

which is conveniently rewritten as

$$\frac{C_{MS}}{C_{MB}}=\frac{M_{TB}}{M_{TS}}$$

where

M_{TS}=total mass of the speaker mesh

and

M_{TB}=total mass of enclosure mesh

As has been indicated, the use of a vented enclosure, appropriately tuned, provides two response peaks in the low frequency range. These are located above and below the resonant frequency ω_0. If k be defined as the peak separation factor, then the upper peak occurs at $k\omega_0$, while the lower peak is found at a frequency corresponding to $\omega_0/_k$.

The separation of the resonance peaks is, for a given speaker unit, a function of enclosure compliance, according to the relationship

$$\left(\frac{k^2-1}{k}\right)^2=\frac{C_{MS}}{C_{MB}}$$

while the enclosure compliance in terms of box volume is given by

$$C_{MB}=\frac{V_B}{\rho c^2}$$

Accordingly, the box volume for a given peak separation factor may be determined, and hence the required port mass M_{TB}, since

$$\frac{M_{TB}}{M_{TS}}=\frac{C_{MS}}{C_{MB}}$$

The mass of the enclosure M_{TB} (for a properly rigid construction) is provided solely by the port, and for a circular port is given approximately by

$$M_{TB}=\frac{\rho t}{S_p}\left(1+0.85\frac{d}{t}\right)$$

where

d=port diameter in cm.

S_p=port area in cm.^{2}

t=thickness or depth of port in cm.

For frequencies above the upper resonance peak $k\omega_0$, the radiation from the speaker unit or units is almost entirely from the front of the cone, the speaker cone serving as a direct radiator substantially unaffected by the enclosure characteristics, assuming that adequate acoustically-absorptive material is employed to line the interior of the enclosure. The present invention is therefore concerned almost exclusively with the response characteristics in the range of frequencies $k\omega_0$ down to $\omega_0/_k$. Also, the invention is particularly directed to providing peak separations substantially in excess of those normally attained in conventional ported enclosures. By way of example, the invention is particularly applicable to peak separation factors wherein k has a value in excess of approximately 1.5, as compared with values of k of the order of 1.1 to 1.2 in ported or vented enclosures of conventional design.

The problem, as has long been recognized, is to provide effective radiation from the port so that the low frequency peak occurring at $\omega_0/_k$ makes a useful contribution to the low frequency response, and at the same time to prevent the peak at $k\omega_0$ from being excessive. The larger the peak separation factor k, the greater the difficulty with both these aspects, hence the use heretofore of relatively small peak separations.

For a given speaker compliance, the box volume is proportional to

$$\left(\frac{k}{k^2-1}\right)^2$$

while the port mass varies as

$$\left(\frac{k^2-1}{k}\right)^2$$

Thus, increasing k requires that M_{TB} be made larger, corresponding to a decrease in port area, if a single aperture is to be used. As a result, for small box volumes, (k greater than about 1.5) the port diameter may be substantially smaller than the effective piston area of the speaker unit or units. Consequently the radiation from the port is relatively insignificant and the performance of the system resembles that of an unported enclosure of inadequate volume.

Instead, therefore, of the usual single port or opening, the present invention makes use of a plurality of spaced apertures or holes which together provide the required M_{TB} and Q for the proper operation of the enclosure with the selected speaker or speakers. While the precise mechanism by which the holes, in the aggregate, provide an enhanced radiation effectiveness as compared with a single port, is not yet completely understood, it is believed that a mutual coupling effect exists which causes the array of holes to function at least to some extent as if the entire region of the array were the port. It is distinctly noticeable in the operation of systems embodying the invention that appreciable aspirating action occurs in the vicinity of the holes due to the velocity of the air therethrough, and it is thought that this action may provide effective coupling to the air mass in the region of the array of apertures so that the radiation effectiveness is greater than that of a single opening of the same M_{TH} as the array.

The holes or apertures comprising the port likewise permit effective control of the Q of the enclosure,

$$\left(Q_2=\frac{\omega_0 M_{TB}}{R_{TB}}\right)$$

since the diameter and number of the holes may be varied to provide the desired resistance. Alternatively, fibrous material of appropriate flow resistance may be used over the holes to provide the correct flow resistance for optimum port damping.

In constructing the port comprising an array of spaced apertures, there are a number of variables that influence the design. The several factors include hole diameter, length, number and spacing. By reason of the fact that the holes are in parallel, the total mass of N holes is $1/N$ times the mass of a single hole.

As has been indicated above, the expression for the mass of a single round hole is given by

$$M_{TH}=\frac{\rho t}{S}\left(1+0.85\frac{d}{t}\right)$$

in c. g. s. units.

Accordingly, the mass of an array of N holes is given by

$$M_T=1/N\frac{\rho t}{S}\left(1+0.85\frac{d}{t}\right)$$

The above relationship of hole diameter, wall thickness and mass reveals that a considerable choice exists in the number of holes, their diameter and length to give the same M_{TH}.

The Q of the holes (the Q of one hole is the same as that of the array) is given approximately by

$$Q_H=2.2d\sqrt{f_0}$$

where d is the diameter in cm. and f_0 is the resonant frequency to which the enclosure is tuned.

It will be noted that the Q of the holes may be controlled by the diameter so that even if no resistive material is used, the required Q and the M_{TH} of the holes may be obtained with a considerable degree of independence since the Q of the hole is independent of depth. For values of Q requiring considerable diameters the wall thickness may be increased or, alternatively, inserts such as tubes or the like may be utilized to provide the required mass. If resistive material is employed over the holes, the small hole diameter that might be required under certain conditions may be rendered unnecessary, the added flow resistance being obtained from the fabric or fibrous material over the holes.

If a supplementary flow resistance is required, over that provided by the holes alone, then the required flow resistance R in Rayls is given by

$$R=.0034\,t\sqrt{f_0}\left(1+0.85\frac{d}{t}\right)\left[\frac{5.6\sqrt{f_0}}{Q_2}-\frac{1}{d}\right]$$

where

t=hole length in inches
d=hole diameter in inches
f_0=resonant frequency

In order to show the improvement in low frequency response that results from the use of the plurality of small apertures as compared with a single opening of conventional practice, expressions have been derived to show the relation, in a conventionally-ported enclosure, of output response at the three frequencies of particular interest in the low frequency region, to the average output in the mid-range of the speaker, at frequencies appreciably above the frequency $k\omega_0$. The response in this latter region is hereinafter referred to as the plateau or flat portion of the frequency response characteristic.

If β is defined as the ratio of the response at a critical frequency to the plateau response, and β_L is the response ratio for the critical frequency ω_0/k, β_M for the frequency ω_0, and β_H for $k\omega_0$, then

$$\beta_L=-\frac{\left(1+j\frac{Q_2}{k}\right)}{\left(\frac{Q_2}{Q_1}+k^2\right)\left(k^2-1+j\frac{k}{Q_2}\right)}$$

$$\beta_M=-\frac{(Q_2-j)}{\left(\frac{1}{Q_1}+\frac{(k^2-1)^2}{k^2}Q_2\right)}$$

$$\beta_H=-\frac{(k+jQ_2k^2)}{\left(\frac{-k^2+1}{k}+j\frac{1}{Q_2}\right)\left(\frac{Q_2}{Q_1}+\frac{1}{k^2}\right)}$$

Thus it is seen that the low frequency response characteristic is a function of the speaker Q (Q_1), the box volume (by reason of the peak separation factor k), and the Q (Q_2) of the port. In general, Q_2 will be larger than Q_1, and k will be greater than 1 but generally not over 2. It will be seen that increasing k to values of the order of 1.5 and above has a marked effect in lowering β_L and in raising β_H, though not significantly altering β_M. To illustrate by typical examples, take the case of a conventionally-ported system wherein k has a value of 1.9, $Q_1=1.1$ and $Q_2=28$. The values of β are

$\beta_L=-14$ db
$\beta_M=-6$ db
$\beta_H=+9$ db

As another example, consider the case where $k=2$, $Q_1=3$ and $Q_2=13$.

Here

$\beta_L=-12$ db
$\beta_M=-7$ db
$\beta_H=+11.5$ db

In both examples, the response characteristic is obviously extremely poor, due to the severe fall-off in response below ω_0 and the excessive peak at $k\omega_0$.

By way of comparison, a speaker system having the same speaker units and box volume as in the first example, when provided with an array of holes as the port, shows a response represented by

$\beta_L=-8$ db
$\beta_M=-4$ db
$\beta_H=+9$ db

Note that β_L has been raised 6 db, β_M has been brought up 2 db, and the upper peak left unchanged. The control of this objectionable resonance is effected by means hereinafter described. This increase at β_L and β_M is due to the increased radiation afforded by the array of holes, as compared with a conventional single aperture of correct dimensions for the enclosure volume.

The improvement in low frequency response due to the increased radiation is defined by a factor γ, and the magnitude of the improvement may be expressed in terms of γ and k as follows:

At $\omega_{0/k}$ the increase is $1+(\gamma-1)k^2$

At ω_0 the increase is γ

At $k\omega_0$ the increase is $1+\left(\frac{\gamma-1}{k^2}\right)$

As a result, it is possible to correlate the design variables of the system so as to permit an appreciable improvement in the equalization of the low frequency response. Thus, the original expression for β_M multiplied by the factor γ will give the improved response ratio. Since the original value for β_M is approximately equal to

$$\left(\frac{k}{k^2-1}\right)^2$$

for large values of Q_2, then if

$$\gamma=\left(\frac{k^2-1}{k}\right)^2$$

the response ratio β_M becomes unity and the actual response at ω_0 is the same as the reference or plateau level.

In the same fashion, the new value of β_L may be found by introducing the value of

$$\gamma=\left(\frac{k^2-1}{k}\right)^2$$

into the expression for β_L. If β_L is to equal 1, then

$$Q_2=\frac{k^2}{\left(k-\frac{2}{k}\right)\left[1-\frac{1}{Q_1\left(k-\frac{2}{k}\right)}\right]}$$

Thus the condition on β_M sets the value of γ while the condition on β_L and the derived γ sets the value of Q_2.

While the values of γ that may be obtained by employing an array of holes as the port, for embodiments in which radiation is occurring both from the front of the speaker cone and from the holes, are probably limited to less than about 1.5, as presently understood, nevertheless appreciable improvement is possible over the usual single port, for values of k in excess of 1.62. Thus, in the case of the first example given, a γ of 1.26 results in the attained improvement of 6 db in β_L and 2 db in β_M.

The provision of a suitable array of holes preferably involves correlating the hole diameter, number of holes, and depth so as to provide, with a hole spacing of the order of $5d$ to $10d$, an array of appreciable over-all area, while still meeting the requirements for M_T and Q_2. The holes may be arranged in various configurations, including triangular, circular and rectangular arrays, depending on the shape of available wall or surface of the enclosure. For speaker systems wherein the array, though occupying an entire surface of the enclosure, is still relatively small in total area because of the small size of the enclosure, as in the embodiment of Fig. 1 where the top wall in a typical system may be only about ½ square foot in area, it is preferable to utilize for the array a surface that may occupy a position normal to and adjacent at least one and preferably two walls of the room when the speaker system is installed.

To control the amplitude of the upper resonance peak occurring at $k\omega_0$ and represented by β_H, which has heretofore been one of the factors preventing the satisfactory use of small enclosures, the partition 20 is employed to divide the interior of the box into separate chambers. This partition is provided with a plurality of spaced apertures **22** which provide communication between the two chambers. Damping means 24 is employed to increase the flow resistance between chambers. Referring to the equivalent circuit diagram, Fig. 6, it will be seen that this partition serves to introduce a shunt path across the cabinet compliance C_{MB}, the effect being that of a damped Helmholtz resonator within the chamber. If the resonator is series tuned to ω_H, then it acts as a shunt path at ω_H, reducing the peak resonance. As a result, instead of a single high peak at $k\omega_0$, two new peaks of lesser magnitude will appear, above and below $k\omega_0$. In practice, it has been found possible to reduce a single 15 db peak to two peaks each approximately 3 db high.

Through the use of a plurality of spaced apertures, plus appropriate damping means, the resonator mass M_{MR} and its damping R_{MR} may readily be controlled to provide, with substantial independence, the proper values to minimize the effect of the upper resonance peak. The calculation of the hole diameter, the number of holes, and the damping required may utilize the same formulae as given above for the porting means of the enclosure.

To consider in detail a specific example of a speaker system embodying the invention, the embodiment of Figs. 1 and 2 may be referred to. This system makes use of four small size speaker units nominally referred to as five inch speakers. By measurement of the voice coil and cone mass, the value of M_{MS} was found to be 1.49 gms. for each speaker. The resonant frequency of the speakers, air load on one side, was found to be approximately 120 cycles. Q_1 was determined to be 1.1.

To provide a highly compact system, a volume of one-half cubic foot was selected, having a compliance of 0.1×10^{-3} cm.^{4} sec.^{2}/gm. The required mass for the holes is then 0.133×10^{-3} gms./cm.^{4}. Using a spacing of slightly over two inches, an array of fifteen 15⁄32″ holes will provide the required M_{TH} and a Q_2 of 28 if the hole length is ½″, corresponding to the wall thickness. The internal resonator or third mesh comprises a partition of ½″ material having 15 holes of 15⁄32″ diameter, with a covering of a fibrous material of 13 Rayls in flow resistance.

The performance of such a system is illustrated in Fig. 7, for the range of frequencies with which the present invention is concerned. The curve in solid line **42** is a typical response of the speaker taken in free field with the speaker mounted at the intersection of three mutually perpendicular surfaces and with the sound pressure level integrated over the surface of that portion of a sphere subtended by the three bounding surfaces. The dot and dash line **44** shows the response obtained with an unported enclosure of the same size and with no internal resonator, while the dashed line curve **46** shows the response with the plurality of ports but without the internal resonator means.

It is readily apparent that the porting means provides a substantial contribution to the low frequency response in the region below about 100 cycles, a 6 db gain being obtained in the vicinity of 60 cycles. At the same time, the internal resonator provides satisfactory control of the upper resonance peak, reducing the 9 db maximum above the plateau region 48 to about 4 db. While the frequency response curve is not shown as fully extended into the high frequency region, it may be remarked that the response of the system, using the same small units that are relied upon for the low frequency response, extends effectively to the region of 10 kc. and above so as to provide a satisfactory balance between the low frequency and the high frequency response.

The present invention accordingly makes possible an extremely compact, low cost loudspeaker system which provides an appreciably extended frequency response as compared with conventional speaker systems normally employed in small radio receiving sets. Since the efficiency of systems embodying the present invention may be made relatively high, it is found that when such systems are attached to existing receivers, the available volume is markedly increased, in addition to the improvement in quality of response.

While the invention has been specifically illustrated in terms of a particular embodiment employing a plurality of transducer units and an alternative form employing a single transducer, it will be understood that the invention is not so limited, but comprehends other forms and constructions embodying the principles and mode of operation of the invention, within the scope of the appended claims. It is also to be understood that the term "loudspeaker means" or "transducer means" comprehends one or more loudspeaker units or driving units, since the invention is applicable to both the single and the multiple unit systems.

We claim:

1. A loudspeaker system comprising an enclosure, transducer means mounted therein with one side of said means in communication with the interior of the enclosure, porting means communicating with the exterior of the enclosure, said porting means comprising a plurality of spaced apertures disposed in an array, the enclosure having a volume corresponding to a peak separation factor in excess of approximately 1.5, and partition means within the enclosure for separating the interior into chambers, the partition means having a plurality of spaced apertures and damping means for restricting flow communication through said apertures between the chambers to minimize the upper resonance peak.

2. A loudspeaker system comprising an enclosure in the shape of a right triangular prism, transducing means comprising a plurality of loudspeaker driving units mounted on a wall of the enclosure, the volume of the enclosure being related to the compliance of the transducer means to provide a peak separation factor approximately equal to 2, porting means in a triangular wall of said enclosure, said porting means comprising an array of apertures disposed in a spacing approximately 5 to 10 times the aperture cross-sectional dimension, the area and the depth of each aperture in the wall providing an equivalent acoustic mass substantially $1/N$ times the

mass required to tune the enclosure substantially to the resonant frequency of the transducer means in the enclosure, where N is the number of apertures in the array, and means within the enclosure for controlling the amplitude of the upper resonance peak, comprising a partition separating the interior into chambers, the partition having a plurality of spaced apertures disposed in an array, the array of apertures in the partition corresponding approximately in number, spacing and depth to the apertures of the porting array, and damping means associated with said apertures of the partition.

3. A loudspeaker system comprising an enclosure in the shape of a right triangular prism of approximately one-half cubic foot volume, transducing means comprising four loudspeaker units mounted on a rectangular wall of the enclosure, the loudspeakers having a free-space resonant frequency higher than approximately one hundred cycles, porting means in a triangular wall of the enclosure, said porting means comprising an array of approximately fifteen holes of the order of one-half inch in diameter spaced approximately two inches apart, and means within the enclosure comprising a partition separating the interior into chambers, the partition having an array of apertures comparable to said porting means, and damping means for minimizing flow through said apertures of the partition.

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