July 13, 1948. F. MASSA 2,445,276

ELECTRODYNAMIC LOUDSPEAKER

Filed May 4, 1945 2 Sheets-Sheet 1

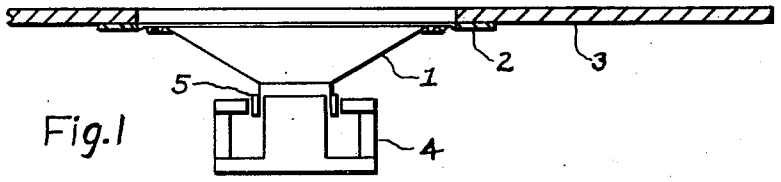


Fig. 1

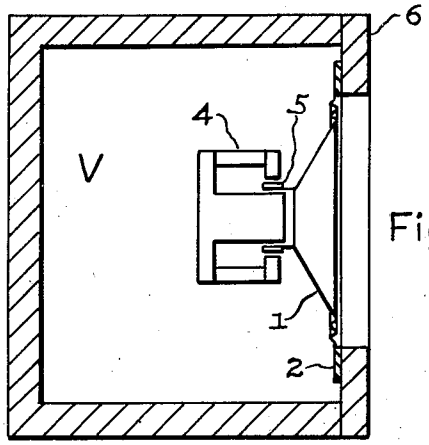


Fig. 2

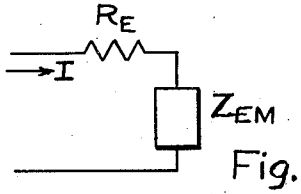


Fig. 3

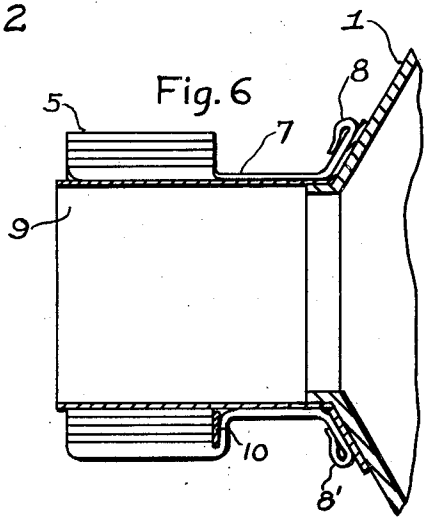


Fig. 6

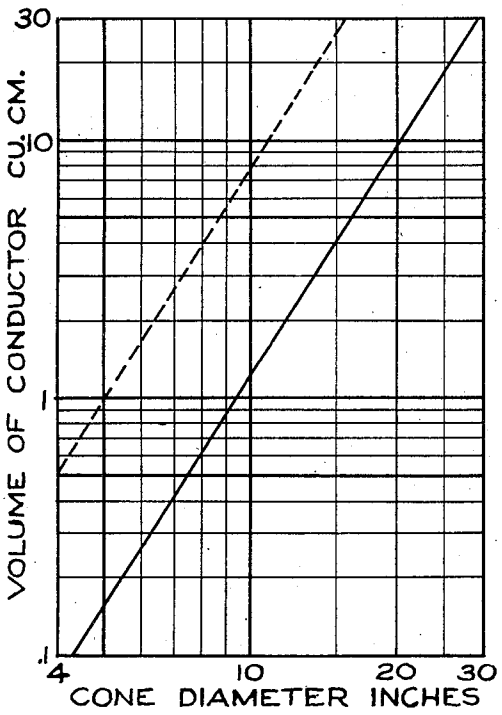


Fig. 5

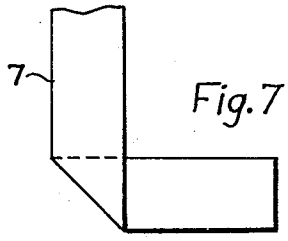


Fig. 7

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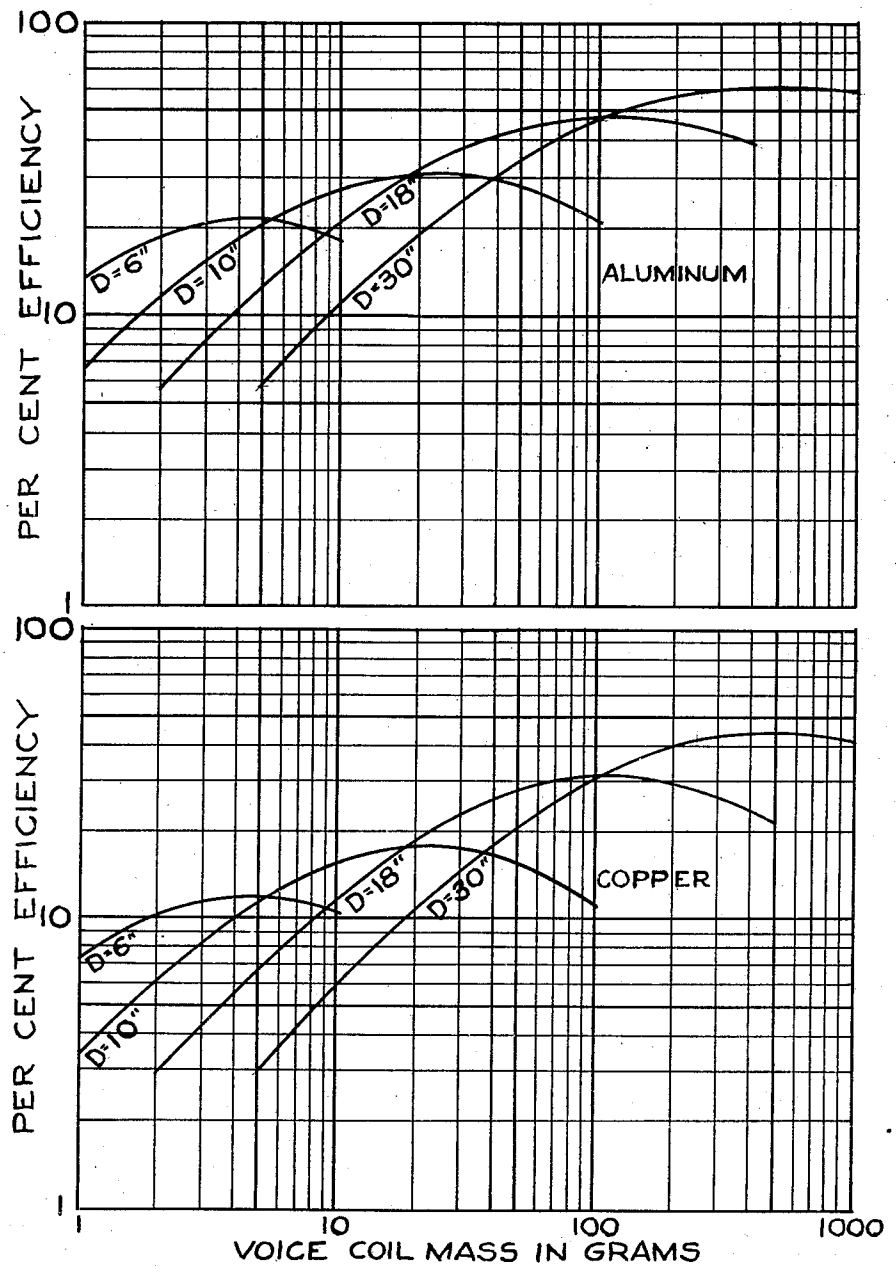


Fig. 4

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UNITED STATES PATENT OFFICE

2,445,276

ELECTRODYNAMIC LOUDSPEAKER

Frank Massa, Cleveland Heights, Ohio

Application May 4, 1945, Serial No. 591,982

8 Claims. (Cl. 179—115.5)

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My invention is concerned with loud speakers, and, more particularly, with the direct-radiator electro-dynamic type of loud speaker. In the electro-dynamic speaker, the driving force is created in a coil of wire supplied with current and residing in a magnetic field. The coil of wire is usually connected to a vibratable cone such that vibrations of the cone are produced corresponding to the variations in the voice coil currents.

It has been universally assumed by loud speaker design engineers that a direct-radiator speaker is inherently a low-efficiency unit because of the inherently low radiation resistance which is presented to a vibrating cone especially at the lower frequencies. This general feeling that it is impossible to obtain high efficiencies in a direct-radiator dynamic speaker has led to the widespread use of horns in installations requiring high efficiencies in the conversion of electrical energy to acoustic energy. Contrary to this accepted general belief, I have found it possible to design direct-radiator speakers that have very high efficiencies, comparable to the efficiencies realized in horn type loud speakers. By employing the teachings of my invention as set forth in this specification, it will be possible to produce low-frequency direct-radiator loud speakers which are not only very much more efficient than the efficiencies now generally obtained from this type of speaker, but it will also be possible to obtain this improved performance in a unit having a much smaller cubic volume than is now needed in the equivalent horn type loud speaker.

For ordinary home radio application, dynamic speakers are now generally employed having efficiencies of the order of 5% and, in many instances, much lower efficiencies. The justification for the use of such low efficiencies has been based on the erroneous assumption that a dynamic speaker is inherently a low-efficiency device, and since audio power was cheap, the direct-radiator speaker was simple to use and economical to build. The important factor that has been overlooked in this line of reasoning is that low-quality transient reproduction will generally result in a low-efficiency speaker. With improved quality of radio broadcasting, the defects resulting from a low-efficiency speaker will cause an increased lack of realism in the sound reproduction which can be greatly improved by employing high-efficiency units. High-efficiency speakers also yield much smoother response characteristics since any peak that may be present in

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the loud speaker system can never exceed 100% efficiency and if, for example, the general efficiency of the speaker is 50%, the peak cannot exceed 3 db. in height. For a 5% efficiency speaker, however, the same peak would be 13 db. in height.

The means that I employ for producing a high-efficiency direct-radiator speaker is to combine into the design a set of unconventional conditions that I have found necessary after long study of the problem. These detailed conditions will be set forth in the specification which follows.

The primary object of my invention is to improve materially the efficiency of a direct-radiator electro-dynamic speaker.

Another object of my invention is to obtain a smoother response-frequency characteristic of a direct-radiator dynamic speaker especially at the lower audio frequencies.

A further object of my invention is to produce a high-efficiency, low-frequency loud speaker which occupies much less space than would be required by a horn type loud speaker having comparable efficiency.

A still further object of my invention is to define the mass of conductor material which must be employed in the construction of the voice coil for various diameters of diaphragms in order that high efficiencies may be realized at the lower audio frequencies.

Another object of my invention is to employ an aluminum voice coil of a specified cubic volume in relation to the diameter of the vibrating diaphragm in order that high efficiencies may be realized.

A still further object of my invention is to provide a voice coil of unique construction such that highest efficiencies may be obtained in a direct-radiator dynamic speaker having a fixed air gap dimension.

Another object of my invention is to define the relationship between flux density, size of diaphragm, and weight of voice coil that will yield high efficiencies for a dynamic speaker over a wide low-frequency range of reproduction.

A further object of my invention is to define the relationship between the cubic volume that may be employed to surround the rear of my new improved speaker such that high efficiency radiation takes place throughout the entire low-frequency range without the necessity of a large baffle, and with a more economical speaker structure.

The novel features that I consider characteris-

tic of my invention are set forth with particularity in the appended claims. The invention, itself, however, both as to its organization and method of operation, as well as advantages thereof, will best be understood from the following description of several embodiments thereof, when read in connection with the accompanying drawings, in which—

Fig. 1 is a simple diagrammatic view of a dynamic speaker mounted in a flat baffle and with reference to which the analysis for the conditions necessary to obtain high efficiences will be made.

Fig. 2 is a diagrammatic view showing a dynamic speaker mounted inside an enclosed volume such that only one side of the vibrating diaphragm may transmit energy to the atmosphere.

Fig. 3 is a circuit illustrating the impediance presented to an electrical circuit by the loud speaker systems shown in Figs. 1 and 2.

Fig. 4 is a set of curves which indicate the efficiencies of a direct-radiator dynamic speaker having various sizes of vibrating diaphragms, as a function of the voice coil mass employed in the construction of the diaphragms. A separate set of curves is shown for the case of aluminum and copper voice coils.

Fig. 5 is a graph showing the optimum volume of aluminum conductor to be employed as a function of cone diameter in order to realize maximum efficiency in the low-frequency region. Another curve is shown indicating the minimum volume of aluminum conductor that is required as a function of cone diameter if a net gain in efficiency is to be realized over the use of copper in the same voice coil structure.

Fig. 6 shows a novel voice coil construction for permitting a maximum amount of conductor to be built economically into a coil of specified linear dimensions.

Fig. 7 illustrates the method of folding the voice coil ribbon to permit the construction of the voice coil terminals indicated in Fig. 6.

Referring more particularly to Fig. 1, the reference character 1 refers to a diaphragm which is flexibly mounted to a supporting rim 2 which, in turn, is fastened to a flat baffle 3, as is conventionally done in loud speaker installations. A magnetic structure 4 furnishes flux in a circular air gap in which is mounted the voice coil 5. The voice coil 5 is rigidly attached to the diaphragm 1 by any of the well-known means employed in the art. The metal framework which ties the magnetic structure 4 to the supporting rim 2 is not shown since this figure is diagrammatic and such physical structures are well-known in the art and form no part of this invention.

In Fig. 2, is shown the same speaker structure described in connection with Fig. 1 except that the speaker is mounted inside a totally enclosed rigid box 6 which provides a net volume of V cubic inches of air behind the diaphragm 1.

In order to show the specific requirements that must be met for the realization of high efficiency in the low-frequency region, reference will be made to the simplified circuit shown in Fig. 3 in which R_E is the electrical resistance in ohms of the voice coil conductor 5 and Z_{EM} is the electrical impedance reflected into the electrical circuit due to the motion of the cone. The magnitude of this reflected mechanical impedance will be different for the operating conditions shown in Figs. 1 and 2, and these differences will be pointed out later. In the circuit of Fig. 3, I represents the current in amperes flowing through the voice coil under

a specified condition of operation. The assumptions which have been made in connection with setting up the electrical circuit shown in Fig. 3 is that the stiffness of the cone suspension in Figs. 1 and 2 is low enough to permit the diaphragm 1 to operate as a pure mass in the frequency region concerned, and in the case of Fig. 2, the volume V is large enough so as not to restrain materially the vibration of the cone 1 over the frequency range of interest.

The magnitude of Z_{EM} in Fig. 3 is given by the expression

$$Z_{EM}=\frac{B^2L^2\times10^{-9}}{R_{MA}+j\omega(M_V+M_C+M_A)} \quad (1)$$

where

B=air gap flux density in gauss
L=length of conductor in voice coil in cms.
R_{MA}=radiation resistance of the vibrating diaphragm in mechanical ohms
$\omega=2\pi f$; f=frequency
M_V=mass of voice coil conductor in grams
M_C=mass of vibrating portion of diaphragm in grams
M_A=effective air load on diaphragm in grams.

When a current of I amperes flows through the voice coil, the electrical power input to the loud speaker system is given by

$$P_E=I^2(R_E+\text{real part of } Z_{EM})$$

$$P_E=I^2\left(R_E+\frac{R_{MA}B^2L^2\times10^{-9}}{R_{MA}^2+\omega^2M_0^2}\right) \text{ watts} \quad (2)$$

where

$$M_0=M_V+M_C+M_A$$

For the current I amperes flowing through the voice coil, a driving force will be generated in the coil equal to

$$F_M=\frac{BLI}{10} \text{ dynes} \quad (3)$$

This force will result in a velocity of the diaphragm equal to

$$V=\frac{F_M}{R_{MA}+j\omega M_0} \text{ cm./sec.} \quad (4)$$

Substituting Equation 3 into Equation 4, it can be shown that the absolute value of the diaphragm velocity squared will be

$$|V|^2=\frac{B^2L^2I^2\times10^{-2}}{R_{MA}^2+\omega^2M_0^2} \text{ cm.}^2/\text{sec.}^2 \quad (5)$$

The acoustic power output from the diaphragm is given by

$$P_A=|V|^2R_{MA} \text{ ergs/sec.} \quad (6)$$

By substituting Equation 5 into Equation 6 and multiplying by 10^{-7} to convert ergs/sec. into watts, the acoustic power output becomes

$$P_A=I^2\left(\frac{R_{MA}B^2L^2\times10^{-9}}{R^2+\omega^2M_0^2}\right) \text{ watts} \quad (7)$$

Since the efficiency is the ratio of the acoustic power output to the electrical power input, the efficiency is equal to the ratio of Equation 7 over Equation 2, which becomes

$$\text{Efficiency}=\frac{R_{MA}B^2L^2\times10^{-9}}{R_E(R_{MA}^2+\omega^2M_0^2)+R_{MA}B^2L^2\times10^{-9}} \quad (8)$$

In order to make Equation 8 more generally applicable to the analysis of a loud speaker in terms of the basic constants of the voice coil con-

ductor, I may substitute for R_E in Equation 8 its equivalent, namely,

$$R_E=\frac{\rho DL^2}{M_V} \tag{9}$$

where

ρ=resistivity of voice coil conductor in ohms/cm.[3]
D=density of voice coil conductor in gms./cc.

After making the above substitution, Equation 8 becomes

$$\text{Efficiency}=\frac{M_V R_{MA} B^2\times 10^{-9}}{\rho D[R_{MA}^2+\omega^2(M_V+M_C+M_A)^2]+M_V R_{MA} B^2\times 10^{-9}} \tag{10}$$

By differentiating Equation 10, allowing Mv to be the variable, I find that the voice coil mass which gives maximum efficiency is given by the expression

$$M_V=\sqrt{(M_V+M_A)^2+\frac{R_{MA}^2}{\omega^2}}\ \text{grams} \tag{11}$$

In order to learn how the various design parameters of a direct-radiator loud speaker affect the efficiency of operation, I have solved Equation 10 for four different effective cone diameters, namely, 6", 10", 18", and 30". The loud speaker was assumed mounted in a large baffle, as shown in Fig. 1. Several voice coil sizes were employed in the computations and both aluminum and copper conductors were investigated. The results of this analysis are indicated in the graphs shown in Fig. 4. The curves plotted in Fig. 4 show the per cent efficiencies realized by the various cone diameters as marked on each curve as a function of the voice coil mass shown along the abscissa. The upper set of curves are for an aluminum voice coil and the lower set of curves represent the same cones driven by copper voice coils. For all of the data plotted in Fig. 4, the air gap flux density is 10,000 gauss. At higher flux densities, the efficiencies are higher and at lower flux densities, the efficiencies are lower than indicated.

In order that the computed efficiencies would have practical significance, I used typical cone masses as follows: 6" diameter=2 grams; 10" diameter=10 grams; 18" diameter=40 grams; and 30" diameter=150 grams. The efficiency curves shown in Fig. 4 apply approximately for the entire lower audio-frequency range in which the wavelength is greater than approximately one-third the diameter of the vibrating diaphragm.

Some rather basic and here-to-fore unknown information is brought to light by an examination of Fig. 4. Some of these facts include:

1. It is possible to produce direct-radiator dynamic speakers having efficiencies in the neighborhood of 50% by employing larger cone diameters and much heavier voice coils than have been generally assumed to be adequate.

2. By simply increasing the diameter of the cone, the efficiency of a particular loud speaker will actually decrease unless the voice coil weight is very materially increased. This decreased efficiency from a large diaphragm has been experimentally observed and has led to the general use of cones having effective vibrating diameters less than 12 inches because it was not recognized that the decreased efficiency produced by the larger cone was the result of a lack of understanding of the necessary voice coil requirements as set forth in this specification. In fact, it has become conventional practice to employ two small speakers

in a radio set to improve the low-frequency performance without recognizing that one large speaker may be designed to be more efficient. For the few exceptional cases where larger cones have been employed, the low efficiency has been tolerated for the sake of obtaining larger power handling capacity (due to less required amplitude of the larger cone for a required output power). The voice coil weights have been far below the values I found necessary for high-efficiency operation.

3. The absolute efficiency of a direct-radiator loud speaker may increase with increasing cone diameters provided the voice coil mass increases approximately as the cube of the increase in the diameter of the cone.

4. The empirical relationship that can be deduced for the conditions shown in Fig. 4 is that in a direct-radiator loud speaker mounted in an infinite baffle, maximum low-frequency efficiency is realized when the mass of the voice coil conductor in grams is equal to approximately $D^3/50$, where D is the effective diameter in inches of the vibrating diaphragm.

5. The region of maximum efficiencies for the various diaphragms is sufficiently broad so that the optimum voice coil mass is, fortunately, not too critical a quantity. However, if the voice coil mass is reduced below approximately one-fifth of the optimum value, the efficiency begins to fall off fairly rapidly. This means that the desirable region within which the voice coil mass should lie in order to profit from the high efficiency possibilities is approximately $D^3/250$ to $D^3/50$ grams, where D is the effective diameter of the voice coil in inches.

6. It is apparent from the information plotted in Fig. 4 that the general practice of employing effective cone diameters up to about 12" for low-frequency reproduction causes considerable sacrifice in the efficiencies that would be realized if larger diameters were used.

7. Aluminum used as the voice coil conductor is much superior to a copper coil of the same mass; however, the volume of an aluminum coil having the same mass as a copper coil would be over three times greater than the volume required for the copper coil, which means that a much more costly magnetic circuit would be required.

A further examination of the data shown in Fig. 4 indicates that it is possible to improve the efficiency, under certain conditions, if aluminum is substituted for copper without increasing the volume of the air gap. In order to show under what conditions this situation is possible, the efficiency data shown in Fig. 4 were converted from voice coil mass as a parameter to the equivalent voice coil volume, and from this new set of data, the solid curve in Fig. 5 was derived. This curve shows the volume of conductor as a function of cone diameter at which the efficiency is the same whether the conductor is aluminum or copper. For voice coil volumes larger than the values indicated by the solid line, an absolute improvement in efficiency will result if aluminum is employed in the construction. The dotted curve in Fig. 5 represents the cubic volume of aluminum necessary to yield the maximum efficiency for various cone diameters and it is merely the plot of the highest points of the efficiency curves shown in the upper half of Fig. 4. The region between the solid and dotted lines, therefore, represents a range of voice coil volumes which will give improved efficiencies with aluminum as the conductor rather than copper. The empirical relation-

ship which may be deduced from these data is that in order to profit from the use of aluminum in the construction of a voice coil, the volume of the voice coil conductor must lie within the approximate range $D^3/850$ cc. to $D^3/135$ cc., where D is the effective diameter of the diaphragm in inches.

The empirical relationships that I have shown specifying the optimum design conditions for voice coils and diaphragms have employed typical cone weights which are representative of the various sizes mentioned. Small deviations from these chosen weights will produce only minor changes in the values shown in Figs. 4 and 5 and, therefore, the ranges of empirical values which I have specified for the voice coil design will be generally correct for engineering purposes.

All the efficiency data described above have been determined for a direct-radiator loud speaker mounted in an infinite baffle, as shown in Fig. 1. If the loud speaker is mounted so that only one side radiates, as shown in Fig. 2, the general set of efficiency curves will be shifted slightly to the left as compared with the curves plotted in Fig. 4. This shift results from the somewhat reduced effective mass and radiation resistance of the vibrating system under this condition of installation. For this condition, the optimum range within which the voice coil mass must lie in order to obtain high efficiency is approximately .7 the values specified under items 4 and 5 in column 6 and also about .7 the values given at the end of the above paragraph. This means that the optimum range of the voice coil mass in grams for the condition of Fig. 2 lies between $D^3/350$ and $D^3/70$, where D is the effective diameter of the vibrating diaphragm in inches. The range of voice coil volume within which improved efficiency will result by the use of aluminum instead of copper for the condition of Fig. 2 becomes $D^3/1200$ to $D^3/190$ cubic centimeters, where D is the effective diaphragm diameter in inches.

In addition to permitting a somewhat reduced voice coil size for the same high efficiency operation, the totally enclosed type of mounting of Fig. 2 will permit a much smaller structure than the rather large baffle which is required for the arrangement of Fig. 1. For the typical cones employed in the determination of the efficiency data described above, I have found that the approximate volume of the enclosure, in order that resonance of the cone and volume shall lie below 80 cycles, must be greater than $200\ D^{5/4}$ cubic inches, where D is the diameter of the cone in inches.

Fig. 6 shows a diagrammatic cross-sectional view through a cone and voice coil assembly indicating a new method for constructing the voice coil in order that practically the entire volume of the coil is occupied by active conductor. The voice coil 5 is wound from a continuous, thin, flat ribbon 7 which is also shown in the plan view of Fig. 7 indicating how the ribbon is folded in order to create a tab which forms the voice coil terminal 8 in Fig. 6. Several layers of the ribbon are wound on a coil form 9 with an insulating film interposed between each layer, and the entire voice coil structure forms a relatively rigid cylinder which is intimately attached to the voice coil form 9. The inside tab of the ribbon 7 is cemented along the voice coil form, as shown in Fig. 6, and the outside tab is folded back and cemented over an insulating strip 10 and then cemented along the voice coil form to establish the second voice coil terminal 8', as indicated. In order to gain maximum advantage from a given air gap, it is generally desirable to make the width of the ribbon employed as the conductor in the voice coil construction of Fig. 6 somewhat greater than the axial length of the air gap in the magnetic structure. In this way, the voice coil will make use of the leakage flux as well as the straight air gap flux in its operation.

Although the quantitative information shown in this specification was derived for specific sets of vibrating diaphragms, it is obvious that minor changes in the results shown would be produced if a somewhat heavier or lighter cone were employed than the particular values chosen. These minor variations, however, will not materially affect the results disclosed. Other obvious changes in some of the details which have been mentioned may be made by those skilled in the art without departing substantially from the teachings of this invention, and I, therefore, desire that my invention shall not be limited except insofar as is made necessary by the prior art and by the spirit of the appended claims.

I claim as my invention:

1. In combination in a loud speaker, a magnetic structure having an air gap, a coil of electrically conducting material located in said air gap, a direct radiating diaphragm rigidly attached to said coil and the assembly flexibly suspended so that it may freely vibrate when driven by forces generated in said coil, the mass in grams of said coil lying in the range between $D^3/250$ and $D^3/50$ where D is the effective diameter in inches of the vibrating area of said diaphragm.

2. The invention set forth in claim 1 characterized in that the effective diameter of the diaphragm is greater than 12 inches.

3. In combination in a loud speaker, a magnetic structure having an air gap, a coil of aluminum conductor located in said air gap, a diaphragm rigidly attached to said coil and the assembly flexibly suspended so that it may freely vibrate when driven by forces generated in said coil, the volume of said conductor lying in the range $D^3/850$ cubic centimeters and $D^3/135$ cubic centimeters, where D is the effective diameter in inches of the vibrating area of said diaphragm.

4. The invention set forth in claim 3 characterized in that the effective diameter of the diaphragm is greater than 12 inches.

5. In combination in a loud speaker, a magnetic structure having an air gap, a coil of electrically conducting material located in said air gap, a diaphragm rigidly attached to said coil and the assembly flexibly suspended so that it may freely vibrate when driven by forces generated in said coil, the mass of said coil lying in the range between $D^3/350$ and $D^3/70$, where D is the effective diameter in inches of the vibrating area of said diaphragm, and an enclosing structure surrounding one side of said diaphragm such that sound radiation takes place from only the unenclosed side of said diaphragm.

6. The invention described in claim 5 further characterized in that the diaphragm has an effective diameter greater than 12 inches and the volume contained within said enclosing structure is greater than $200D^{5/4}$ cubic inches, where D is the effective diameter in inches of the vibrating area of said diaphragm.

7. In combination in a loud speaker, a magnetic structure having an air gap, a coil of aluminum conductor located in said air gap, a diaphragm rigidly attached to said coil and the assembly flexibly suspended so that it may freely

vibrate when driven by forces generated in said coil, the volume of said conductor lying in the range $D^3/1200$ cubic centimeters and $D^3/190$ cubic centimeters, where D is the effective diameter in inches of the vibrating area of said diaphragm, and an enclosing structure surrounding one side of said diaphragm such that sound radiation takes place from only the unenclosed side of said diaphragm.

8. The invention described in claim 7 further characterized in that the diaphragm has an effective diameter greater than 12 inches and the volume contained within enclosing structure is greater than $200D^{5/4}$ cubic inches, where D is the effective diameter in inches of the vibrating area of said diaphragm.

FRANK MASSA.

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