

Aug. 22, 1944.

E. E. MOTT

2,356,262

ACOUSTIC DEVICE

Filed Aug. 3, 1940

3 Sheets-Sheet 1

FIG. 1

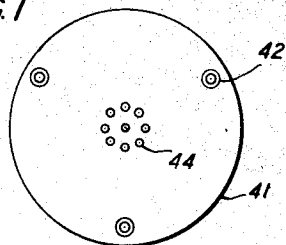


FIG. 2

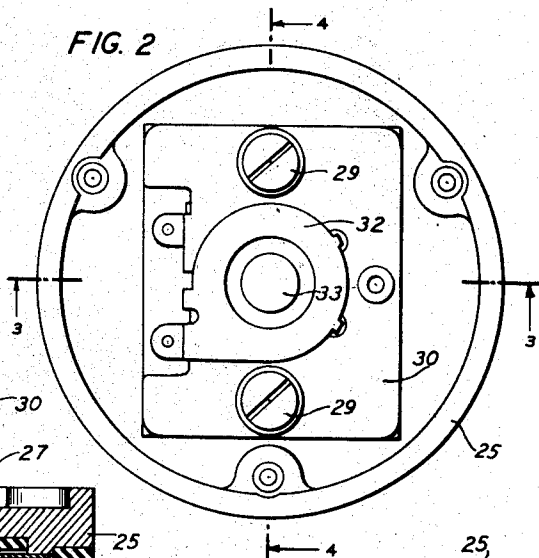


FIG. 3

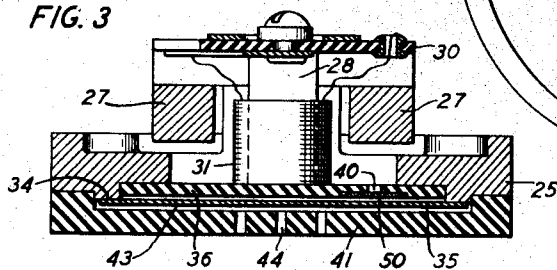


FIG. 7

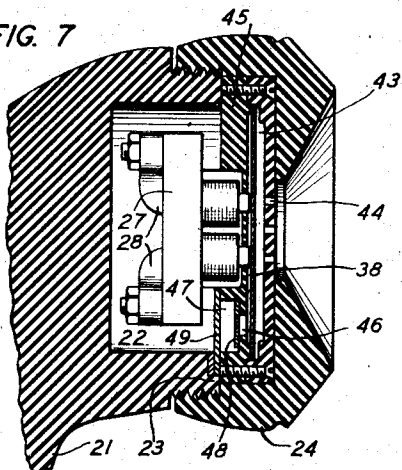


FIG. 4

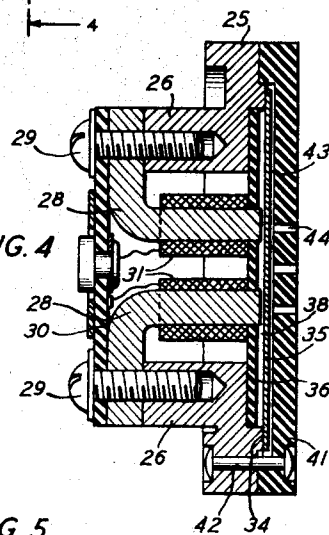


FIG. 5

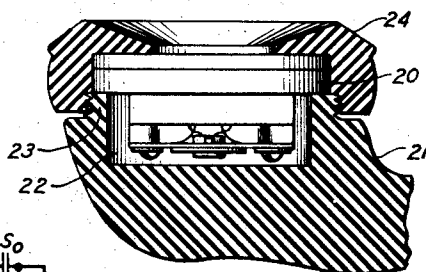


FIG. 6

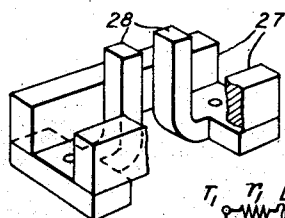
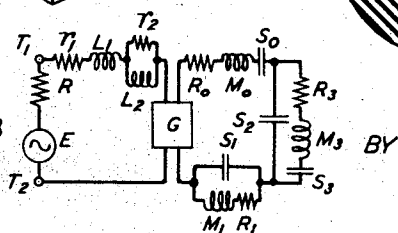


FIG. 8



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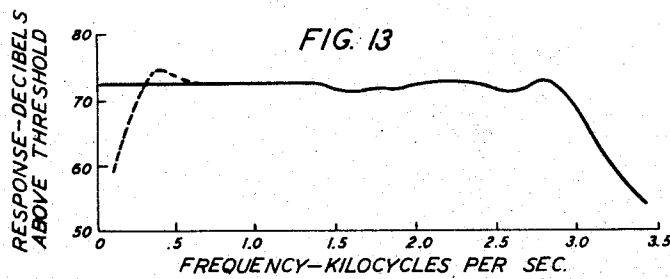
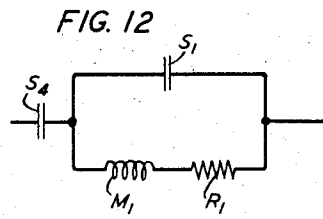
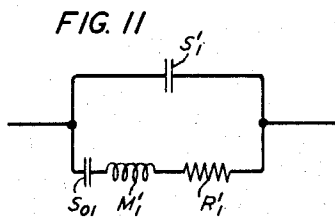
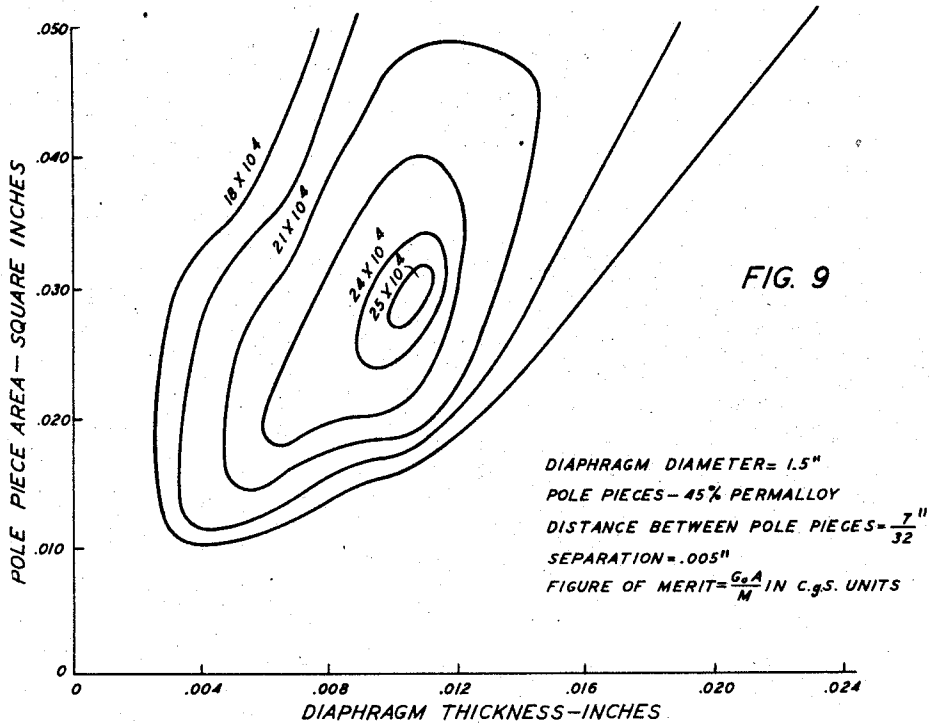
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3 Sheets-Sheet 2



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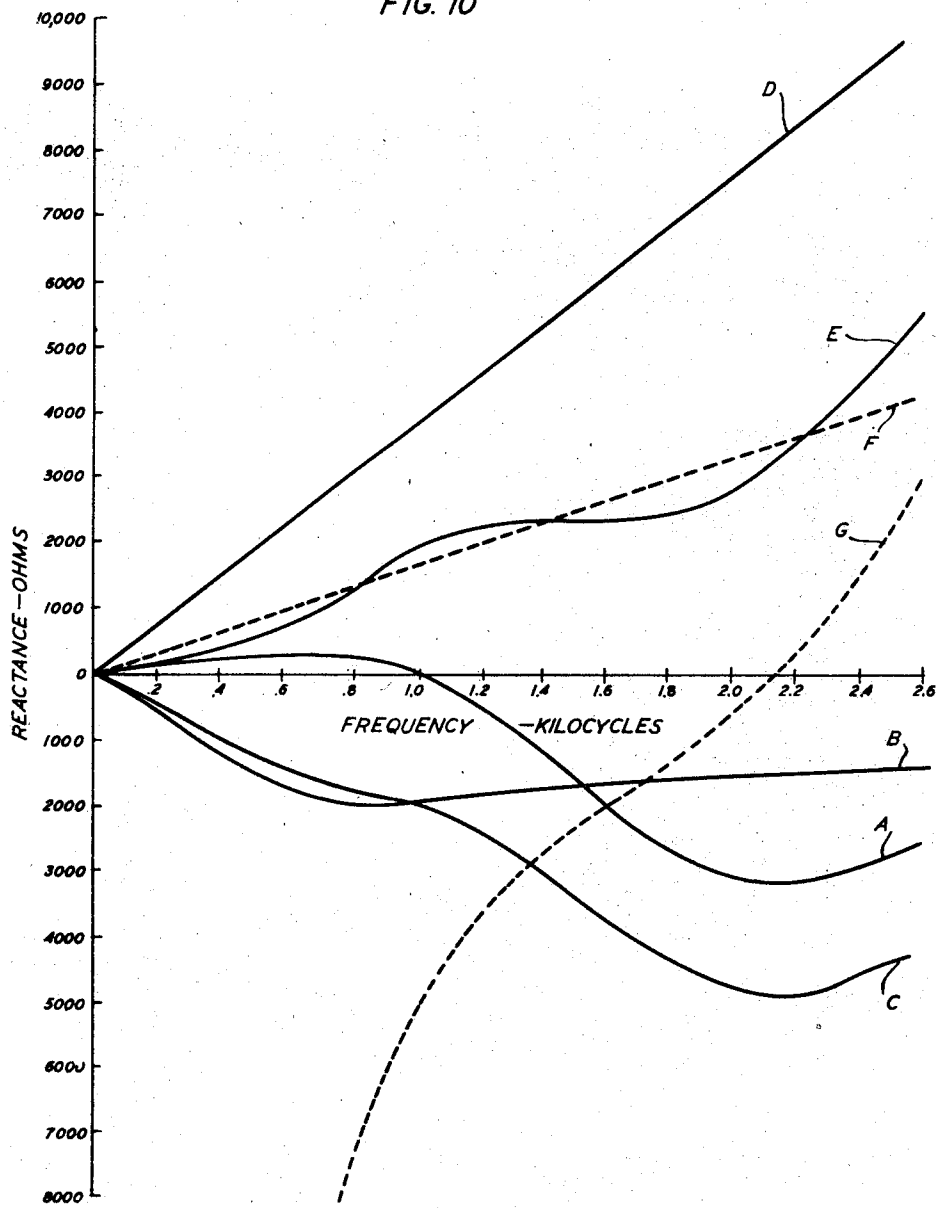
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FIG. 10



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UNITED STATES PATENT OFFICE

2,356,262

ACOUSTIC DEVICE

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Application August 3, 1940, Serial No. 350,741

9 Claims. (Cl. 179—180)

This application is a continuation of the application Serial No. 93,792, filed August 1, 1936, of Louis A. Morrison and Edward E. Mott, which resulted in Patent 2,220,942, granted Nov. 12, 1940.

This invention relates to acoustic devices, and, more particularly, to telephone receivers of the magnetic armature or diaphragm type.

Objects of the invention are to increase the sensitivity of such devices; to extend the frequency range of their efficient operation; and to improve the uniformity of their responses in the operating range.

These objects are accomplished in part by the provision of an improved magnetic circuit in which the structural proportions of the elements and the magnetic properties of the materials are coordinated, in a manner hereinafter described, to provide an optimum force factor. In part, they are accomplished by the use of arrangements which not only provide an adequate degree of damping, but also serve to diminish substantially the effect of the inertia of the diaphragm.

An important feature of the invention lies in the mutual proportioning of the cross-sectional area of the pole-pieces of the magnet system, the thickness of the diaphragm or armature, and the magnitude of the polarizing flux whereby the ratio of the force factor to the effective moving mass is substantially the maximum obtainable for the materials of the magnetic circuit.

Another feature is the provision of improved magnetic alloys for the several parts of the magnetic circuit, the material of each part being particularly adapted to the function thereof.

A further feature resides in a relatively thick and rigid diaphragm having a high magnetic efficiency in combination with damping means proportioned to diminish substantially the effective mass.

An additional feature includes a freely supported diaphragm, whereby variable mechanical stresses due to temperature changes and the like are avoided and stability of the operating characteristic is secured together with structural arrangements for securing and maintaining accurate relative positioning of the diaphragm and the pole-pieces.

Other and further features will be evident from the description which follows hereinafter.

A more complete understanding of the invention will be obtained from the following detailed description, taken in conjunction with the appended drawings, wherein:

Fig. 1 is a top plan view of a telephone receiver or receiver unit embodying the invention;

Fig. 2 is an enlarged rear plan view of the device of Fig. 1;

Fig. 3 is a sectional view of the device of Fig. 1, taken along the line 3—3 of Fig. 2;

Fig. 4 is another sectional view of the device of Fig. 1, taken along the line 4—4 of Fig. 2;

Fig. 5 shows the device of Fig. 1 associated with the receiver end of a hand telephone or handset;

Fig. 6 shows in perspective and partly broken away the pole-piece and magnet assembly of the device of Fig. 1;

Fig. 7 discloses, embodied in a hand telephone, a modification of the invention;

Fig. 8 is an electrical circuit analogy of the electrical and acoustical elements embodied in a receiver in accordance with this invention;

Fig. 9 shows a set of contour curves illustrating the variation in figure of merit of telephone receivers with variation in the pole face area and the diaphragm thickness thereof for a magnetic circuit of a given air-gap length and given magnetic materials;

Fig. 10 shows electrical and acoustical characteristic curves for a telephone receiver in accordance with the invention;

Fig. 11 is a schematic of the damping elements of the device of Fig. 7;

Fig. 12 is a schematic equivalent of Fig. 11;

Fig. 13 is an amplitude-frequency response characteristic of a telephone receiver in accordance with this invention, the dotted line indicating the effect of air leakage between the receiver and the user's ear.

The device illustrated in Figs. 1 to 6 is a telephone receiver comprising a unitary receiver assembly 20, adapted for mounting in the receiver end of a handset or other type of receiver case and to be held in position by the receiver cap. The assembly of the device in a handset is illustrated in Fig. 5 in which 21 is a portion of a handset frame, the receiver end of which is provided with a recess 22 surrounded by a raised annular rim 23 on which the assembly rests. Receiver cap 24 threaded to the annular rim 23 clamps the device in position.

The central feature of the unit 20 is a rigid annular foundation frame 25 to which the other elements of the assembly are attached. This frame is preferably of non-magnetic metal, such as aluminum or zinc alloy, and may be of die cast construction.

Bosses 26, projecting from the back of frame 25, support a unitary magnet and pole-piece system, the detailed construction of which is shown in Fig. 6. The magnet structure comprises one or two rectangular-section straight bar permanent magnets 27, and two L-shaped pole-pieces 28, also, preferably, of rectangular-section and having flanges extending sideways at one end. If two magnets are used, they are laid parallel to each other with their like magnetic poles ad-

jacent and are welded at their ends to the flanges of the pole-pieces, the complete assembly having the form indicated. The unitary structure is mounted on frame 25 with the cross portions of the pole-pieces resting on projecting bosses 28 and secured thereto by screws 29. Terminal plate 30 of insulating material extending across the rear of the assembly is also secured in position by screws 29. The ends of the pole-pieces pass between the magnets and project into the central aperture of the foundation frame. Speech current coils 31 are mounted on the pole-pieces and have their ends brought out to concentric contact elements 32 and 33 mounted on plate 30.

The front face of the foundation frame 25 is provided with an annular ridge 34 surrounding a central recessed portion. A flat circular diaphragm 35 of magnetic material is supported at its periphery by the ridge, and is held in position by the attraction of the pole-pieces. The diaphragm is not mechanically clamped and is therefore free to expand and contract in response to temperature changes without being subjected to mechanical stresses. The form of the supporting frame 25 and the method of supporting the magnetic elements therefrom facilitate accurate machining and assembly of the parts and ensure the establishment and maintenance of a precise separation between the diaphragm and the faces of the pole-pieces.

A damping plate 36 of insulating material, provided with suitable close fitting apertures through which pole-pieces 28 project, is inserted in the central recessed portion of frame 25 to which it may be riveted, cemented, bonded or otherwise secured. The damping effect is obtained by the use of a plurality of very narrow air leakage paths leading through plate 36 from the air chamber 38 between the plate and the diaphragm. In the present structure, these are provided by an aperture 40 in the damping plate over which is laid one or more strips of silk fabric 50. Other known arrangements for this purpose may also be used, such as any fibrous or porous material through which the air may flow against frictional forces. The front of the diaphragm is enclosed by a recessed cover plate 41 of insulating material, which is secured to frame 25 by rivets 42. The recessed portion of the cover plate is large enough in diameter to clear the diaphragm and is deep enough to provide an air chamber 43 of proper dimensions in front thereof. A group of small, centrally located apertures 44 provide sound wave outlets from air chamber 43.

A typical magnet structure would comprise parts approximately of the following compositions and dimensions: permanent magnets of 35 per cent cobalt steel, 1.25 inches long, and one-sixteenth of a square inch in cross-sectional area; pole-pieces of a nickel-iron alloy in the approximate proportions 45:55, each having a cross-sectional area of .031 square inch; a diaphragm of cobalt iron-vanadium alloy in the approximate proportions 49:49:2, its thickness being .011 inch, its diameter 1.46 inches and its normal air-gap from the pole faces substantially six-thousandths of an inch.

The receiver illustrated in Fig. 7 is, in general, similar to that of the preceding figures, but differs therefrom in certain features of the mechanical structure and in the arrangement of the acoustic damping elements. The foundation frame 45 is of insulating material instead of metal, and may consist of a molded phenol plas-

tic part. It is similar in shape to the frame 25 of the preceding example, but includes the damping plate back of the diaphragm as an integral element with apertures molded to receive the magnet pole-pieces. The magnet system and the diaphragm are of the same construction, and are supported in the manner already described. The complete assembly unit is adapted for mounting in the same way as that of Figs. 1 to 6, and may be interchangeable therewith. In the figure, it is shown mounted in a handset telephone.

For the purpose of damping, an aperture 46 in the front of frame 45 communicates with a chamber 47 formed in the rear of the frame. A disc 48 positioned across the rear of aperture 46 and provided with a plurality of fine holes or slots provides the desired acoustic resistance. Chamber 47 is closed by a back plate 49, cemented in place, thereby limiting the motion of the air through the acoustic resistance and modifying the action thereof. In an experimental model of this receiver, the magnetic structure was the same as that of the previous example except that a diaphragm of slightly larger diameter, 1.565 inches, was used.

The invention resides, in part, in the coordination of the structural proportions of the mechanical elements with the magnetic characteristics of the materials of the system and with the acoustic elements of the system. The mechanical structures illustrated in Figs. 1 to 7 are of importance in that they embody features whereby the principles of the coordination may be applied with a high degree of accuracy, and whereby the stability of the improved operating characteristics is ensured. The manner in which the proportions of the system are coordinated will be more readily understood and appreciated from the following considerations.

The function of a telephone receiver of the type described is to produce a pressure variation in the cavity of the ear to which it is applied, which follows as faithfully as possible the variations of the speech current applied to the device. Since the ear cavity forms a substantially closed air space directly coupled to the diaphragm of the receiver, the pressure variation will be dependent on the amplitude of the diaphragm motion rather than on its velocity. While the air space enclosed by the application of a receiver to the ear is, in general, not completely closed, we have found that the effect of the air leakage paths is large only at quite low frequencies, and is barely noticeable at frequencies above 200 or 300 cycles per second. It is assumed, of course, that the instrument is held fairly firmly against the ear.

For the purpose of examining the response characteristic of any given receiver, we have found that it is permissible to replace the ear cavity by a rigid-walled chamber of six cubic centimeters volume coupled directly to the outlet aperture in the receiver cap and having no outlet to the external air. The pressure variation measured in this cavity is a reliable measure of the sensitivity of the receiver and furnishes an accurate basis for the comparison of different designs. The use of rigid walls in the chamber is justified by the fact that the energy absorbed by the walls of the ear cavity is negligibly small compared with the energy dissipated elsewhere in the receiver system. The volume six cubic centimeters, has been found by many measurements to be a good approximation to the normal human ear, and is, therefore, representative of the conditions under which the receiver will most frequently operate.

The system comprising the receiver and the closed chamber load is one which lends itself to analysis both experimentally and mathematically. For this purpose, the receiver shown in Figs. 1 to 6 may be represented schematically by the diagram of Fig. 8. Here T_1 and T_2 are the input terminals of the receiver, to which are connected an oscillation source of voltage E and internal resistance R . The receiver winding impedance, measured with the diaphragm held fast, is represented by resistances r_1 and r_2 and inductances L_1 and L_2 . Resistance r_1 is the direct current resistance of the winding, inductance L_1 is the inductance of that part of the winding which is substantially uncoupled to the magnetic circuit, inductance L_2 is the inductance of the coupled, or effective, part of the winding, and resistance r_2 represents the eddy current loss in the magnetic elements. The electrical part of the circuit is coupled to the mechanical-acoustical part by virtue of the force factor which is indicated schematically by the element G . The elements of the mechanical-acoustical part of the system are indicated in the diagram as follows: M_0 denotes the effective mass of the diaphragm, S_0 its effective flexural stiffness, and R_0 the mechanical resistance due to hysteresis. The stiffness of the air chamber 38 back of the diaphragm is represented by S_1 and the acoustic impedance of the leakage path through damping element 40 by resistance R_1 and mass M_1 . S_2 denotes the stiffness of the air chamber 43 in front of the diaphragm, R_2 and M_2 are respectively the resistance and mass of the combined outlet apertures 44, and S_3 is the stiffness of the enclosed ear cavity which, for the reasons indicated, is taken as that of an air volume of six cubic centimeters connected to apertures 44. Resistances R_0 and R_1 are sufficiently small in comparison with the other resistances of the system so that they do not materially affect the response.

At very low frequencies, where the reactances of the mass and inductance elements are negligibly small, it may be shown that the amplitude of the displacement of the diaphragm is given by

$$a = \frac{IG}{S_0 + \frac{S_2 S_3}{S_2 + S_3}} \quad (1)$$

wherein a denotes the amplitude, G the magnitude of the force factor, and I the amplitude of the current in the electrical circuit, all values being in c. g. s. units. S_1 may be omitted because it is negligibly small. If the masses of the system could be eliminated, no damping would be necessary, since, in the absence of mechanical resistance, the fixed proportionality between the current and the displacement expressed by Equation 1 would then hold at all frequencies.

Because of the mass of the diaphragm, the amplitude of the displacement varies with frequency and exhibits a maximum at a resonance frequency determined substantially by the mass M_0 and the combined stiffnesses S_0 , S_2 and S_3 . By proper proportioning of the damping, the amplitude at this resonance may be made equal to the low frequency value given by Equation 1. At frequencies below resonance, the displacement then remains substantially constant, but at higher frequencies it tends to fall off very rapidly. The resonance frequency of the diaphragm is, therefore, a measure of the frequency range through which uniform response can be maintained. An extension of the frequency range above the diaphragm resonance is obtained by proportioning the outlet apertures 44, which couple the front of the diaphragm with

the ear cavity, so that the mass of air therein resonates with the stiffness of the ear cavity and the front air chamber 43 at a higher frequency. This resonant system corresponds to the loop S_2 , M_2 , R_2 , in Fig. 8. However, to maintain uniformity of the response over the extended range, the above noted ear cavity resonance frequency must bear a substantially fixed proportion to the resonance frequency of the diaphragm, which proportion I have found to be substantially equal to 1:2. The utility of the diaphragm resonance frequency as a measure of the operating range is, therefore, not affected by modifications of the acoustic system.

The diaphragm resonance frequency is given by the relationship,

$$\omega_0^2 = \frac{1}{M_0} \left(S_0 + \frac{S_2 S_3}{S_2 + S_3} \right) \quad (2)$$

where ω_0 denotes 2π times the resonance frequency. From Equations 1 and 2 is obtained,

$$\frac{a\omega_0^2}{I} = \frac{G}{M_0} \quad (3)$$

the left-hand side of which represents the product of the displacement per unit current multiplied by the square of the frequency range, and the right-hand side of which is a constant for a given structure. Since the performance of a receiver is gauged by the combination of the two factors, sensitivity and frequency range, it will be seen from Equation 3 that a high level of performance depends not on the magnitude of the force factor alone, but on the ratio of this quantity to the effective mass of the diaphragm.

In Equations 1 and 3, the response is indicated by the amplitude of the diaphragm displacement. More correctly, it should be represented by the pressure increment in the ear cavity represented by the stiffness S_3 . At low frequencies, and hence at all frequencies in the response range of a properly damped device, the increment of pressure due to the diaphragm displacement is given by

$$\frac{p}{P} = \gamma \frac{Aa}{V_2 + V_3} \quad (4)$$

where p denotes the pressure increment in the ear cavity, P the normal atmospheric pressure, γ the adiabatic constant for air, A the effective diaphragm area, and V_2 and V_3 respectively the volumes of the air chamber 43 in front of the diaphragm and of the normal ear cavity. By means of Equations 3 and 4, a modified performance equation is obtained, namely,

$$\frac{p}{I\omega_0^2} = \frac{P\gamma}{V_2 + V_3} \frac{GA}{M_0} \quad (5)$$

in which the sensitivity of the device appears as the pressure increment in the ear cavity per unit of current in the receiver windings. The quantities P and γ are physical constants and, since the volume V_2 will generally be small compared with V_3 , the sum of the two volumes may be taken as substantially equal to V_3 , which may also be considered to be a physical constant. The ratio $P\gamma/(V_2 + V_3)$ is, therefore, a constant which is independent of the receiver design.

It may, further, be shown that the force factor G , which is defined as the ratio of the mechanical force produced to the magnitude of the current producing it, may be expressed in terms of the

magnetic flux and the number of turns in the receiver winding by the equation,

$$G = n \frac{d\phi}{da} = nG_0 \quad (6)$$

where n is the number of turns and G_0 , or

$$\frac{d\phi}{da}$$

is the rate at which the total flux interlinking the diaphragm and the pole-pieces varies with the displacement. Substituting this value of G in Equation 5 and dividing both sides by n gives the relationship,

$$\left(\frac{p}{In}\right)\omega^2 = \frac{P\gamma}{V_1 + V_2} \frac{AG_0}{M_0} \quad (7)$$

in which the sensitivity is expressed as the more basic ratio of the acoustic pressure to the ampere turns of the winding. The factor G_0 appearing on the right-hand side is likewise a basic parameter of the magnetic structure since it depends wholly on the geometry of the structure and the magnetic properties of the materials. The expression,

$$\frac{AG_0}{M_0} \quad (8)$$

may, therefore, be regarded as a fundamental figure of merit by means of which the performances of different types of telephone receivers may be compared. In the case of receivers, such as those of the invention, in which magnetic diaphragms of uniform thickness are used, the ratio of the effective area to the effective mass is substantially inversely proportional to the diaphragm thickness, the densities of the various ferro-magnetic materials being approximately alike. The figure of merit is therefore proportional to the ratio of the force factor to the diaphragm thickness.

To secure a high figure of merit, it is desirable that the diaphragm have a large effective area and a small effective mass, and that the flux traversing the magnetic circuit vary rapidly with the diaphragm displacement. The value of the figure of merit is dependent on the length of the air-gap, the cross-sectional area of the pole-pieces and the thickness of the diaphragm, all of which may be varied independently. As the air-gap is decreased, the figure of merit increases continuously, but practical considerations of manufacture and of stability of operation limit the minimum length of air-gap, and hence, also, the improvement in the figure of merit that can be obtained in this way.

From an extensive series of measurements of the force factor in structures employing electromagnets as the source of polarizing flux I have found that, for a given set of structural dimensions, air-gap, pole face area and diaphragm thickness, the figure of merit exhibits a maximum for a particular value of the polar magnetizing force. Further, when the diaphragm thickness is varied independently, the magnetizing force being adjusted in each case to the optimum value, a maximum of the figure of merit appears for a particular diaphragm thickness and, likewise, when the pole face area is varied a maximum is developed for a particular area. I have also found that the figure of merit reaches a grand maximum for a particular combination of these dimensions. This represents an absolute maximum of the figure obtainable with a given air-gap and given materials in the pole-pieces and diaphragm. To achieve the maximum there

is required a proper coordination of the three quantities, polarizing flux, pole face area, and diaphragm thickness. Coordination of the pole face area and the diaphragm thickness without regard to the polarizing flux will result in a partial maximum with respect to variations of these quantities, but to obtain the absolute maximum it is necessary that the polarizing flux also have a value for optimum effect.

In the experimental work referred to, the rate of change of the magnetic flux was measured directly by giving the diaphragm a sudden minute displacement of accurately measured magnitude and observing the resulting deflection of a calibrated ballistic galvanometer connected to the receiver coil terminals. This method proved sensitive and accurate and sufficiently rapid to permit a large number of conditions to be examined in a very short time. In the tests, the pole face area, the diaphragm thickness and the length of air-gap were systematically varied and a wide range of magnetic materials was investigated. The variation of the figure of merit found in one series of tests is illustrated by the closed curves of Fig. 9. Each curve or contour line corresponds to a fixed value of the figure of merit and the coordinates represent the various combinations of pole area and diaphragm thickness which provide this value. The intersections of the contour lines with horizontal lines parallel to the thickness axis give successive values of the figure of merit for different diaphragm thicknesses, and the intersections with vertical lines give the values for different pole face areas.

In the series of tests resulting in the curves of Fig. 9, the magnetic structure used was generally similar in configuration and in materials of construction to that of the receiver shown in Figs. 1 to 6, except that a slightly smaller air-gap of five thousandths of an inch was used. The maximum value of the figure of merit was somewhat greater than 25×10^4 in c. g. s. units and was obtained with a pole face area of approximately .030 square inch, and a diaphragm thickness of approximately eleven thousandths of an inch. The polarizing flux density in the pole-pieces was approximately 6000 lines per square centimeter and in the diaphragm approximately 14,000. An increase of the normal air-gap to six thousandths of an inch was found to have substantially no effect on the optimum dimensional relationship and resulted only in a slight diminution of the maximum figure of merit.

In order that the optimum conditions might be realized in a corresponding structure employing a permanent magnet, the size and strength of the permanent magnet were so chosen as to produce the same polarizing flux in the pole-pieces and air-gap as was produced by the optimum magnetizing current in the experimental electromagnet system. This was satisfactorily accomplished by the use of a pair of 35 per cent cobalt-steel magnets, 1.25 inches long and one-sixteenth of a square inch in cross-sectional area, magnetized to a stable condition in accordance with standard practices. Further tests were made upon the permanent magnet structure by superimposing a variable magnetomotive force upon the magnetic circuit for the purpose of varying the flux. These showed that the optimum flux condition was substantially realized.

The physical conditions that give rise to the optimum dimensional relationships are of a complex character and do not lend themselves readily to analysis. However, the existence of the

grand maximum of the figure of merit has been thoroughly established by the tests referred to above. Moreover, the tests show that the grand maximum has the character of an absolute maximum which, for given magnetic materials and for a given air-gap cannot be exceeded, except, possibly, to the extent of second order variations, by any changes in the configuration or proportions of the structure or of the value of the polarizing flux. With different magnetic materials, other optimum dimensional relationships than those indicated by Fig. 9 may be found to hold. The tests referred to above have shown that, in general, the optimum dimensional relationships involve a diaphragm thickness much greater than has heretofore been used. For example, when diaphragms of ordinary magnetic iron are used, the optimum thickness is found to be approximately fourteen-thousandths of an inch or greater. The optimum dimensions and the optimum polarizing flux for any particular combination of materials may be determined by following the experimental procedure outlined above.

In the present receiver the diaphragm material is characterized by a permeability which retains a high value at high flux densities. It is thought that this characteristic may, at least in part, account for the fact that the optimum diaphragm thickness is less than for other magnetic materials.

From the general formula for the attraction between the faces of an air-gap in a magnetic circuit, it can be shown that the force factor G is expressed approximately in terms of the magnetic fluxes by the equation,

$$G = n \frac{d\phi}{da} = \frac{B_0}{4\pi} \frac{d\phi}{di} \quad (9)$$

where B_0 is the polarizing flux density in the air-gap and $d\phi/di$ is the rate of variation of the flux with current in the receiver winding. The latter quantity is inversely proportional to the reluctance of the magnetic path traversed by the alternating flux produced by oscillating currents in the receiver windings. It follows, then, that the figure of merit expressed by Formula 8 is proportional to the ratio of the polarizing flux density to the alternating current reluctance of the magnetic circuit and inversely proportional to the diaphragm thickness. These quantities influence each other mutually in a highly complex manner which prevents a mathematical analysis of the conditions existing at the optimum relationship. The experimental attack outlined above, therefore, represents the best available method for obtaining accurate data.

At the grand maximum, the variation of the figure of merit with the pole face and diaphragm dimensions is not very rapid and a reasonable latitude in the dimensions of these parts may be permitted without noticeable sacrifice of the sensitivity or frequency range. For the magnetic circuit structure already described the diaphragm thickness of .011 inch and the pole face area of .031 square inch correspond satisfactorily to the values for the maximum figure of merit when the normal air-gap is about .006 to .0065 inch. Under these conditions a figure of merit of the order of 250,000 in c. g. s. units is obtained, which is about twice as great as the value for earlier receivers of similar type.

The relatively great diaphragm thickness for maximum force factor to mass ratio provides sufficient rigidity so that the diaphragm may be

supported freely at its periphery without danger of being pulled into contact with the pole faces by the attraction due to the polarizing flux. The rigidity is also sufficient to ensure the maintenance of a fixed normal air-gap thereby stabilizing the operating characteristics of the system. The absence of edge clamping results in a simpler mode of flexure of the diaphragm under the superimposed force of the speech currents which considerably increases the effective area and the total volume of the air displaced.

While the pole-pieces have been described hereinabove as L-shaped with side flanges, it is to be understood that considerable variation is permissible in structure. Thus, the side flanges may be omitted, in which case the bar magnets would preferably be in contact with the short leg of the pole-pieces. On the other hand, the pole-pieces might be in the form of an inverted T, in which case the bar magnets would rest on the side members of the T in the manner shown and would naturally be somewhat shorter. In the case of either of these modifications, it would be necessary to have the other dimensions modified in order to get the desired force factor to diaphragm thickness ratio. The principle to be followed in making such redesign will be evident from this specification.

A further improvement in the over-all performance of the receivers of the invention is obtained by the use of damping arrangements which not only provide the energy dissipation necessary for uniform response, but at the same time substantially diminish the effective mass of the diaphragm. This result is achieved by the proper coordination of the acoustic and electrical damping whereby the negative reactances introduced by the separate means are of a complementary character, their sum increasing substantially linearly with frequency throughout the greater portion of the operating range.

Referring to Fig. 8, the acoustic damping elements of the system are represented by resistance R_1 , mass M_1 and stiffness S_1 . If this combination is proportioned so that R_1 is approximately equal to the square root of the product $M_1 S_1$, its total effective reactance will vary with frequency in the general manner indicated by curve A of Fig. 10. The characteristic features of the variation are a low value of reactance throughout a wide range at low frequencies and a maximum negative value at a relatively high frequency close to the resonance frequency of mass M_1 with stiffness S_1 .

Another component of negative reactance is introduced by virtue of the coupling to the electrical circuit through the force factor. The impedance introduced into the mechanical-acoustical portion of the circuit in this way is equal to

$$\frac{G^2}{Z_0}$$

which is the impedance of a network of inverse character to the electrical impedance R , r_1 , L_1 , r_2 , L_2 . The reactance portion of the introduced impedance has a characteristic variation of the type shown by curve B of Fig. 10 and is negative in sign. By proper choice of the electrical coefficients, curve B may be made substantially complementary to curve A, giving a total effective reactance of the type indicated by curve C. This curve represents a negative reactance which increases substantially linearly with frequency up to or beyond the resonance determined by M_1 and S_1 . The frequency variation of the reactance is of the same character as that of the reactance of

a physical mass, but the sign of the reactance is reversed. The damping elements therefore may be considered as contributing a negative mass which is nearly constant over the operating range and which, being in series with the diaphragm mass, diminishes the total effective mass of the system. Physically a negative mass would have the property of producing an inertia reaction which acts in the direction of the acceleration instead of in opposition thereto, and may be considered to be present in any system where such a condition exists.

Heretofore in receivers of the magnetic diaphragm type, the force factors have been so low that the requisite values of the transferred impedance to provide the desired characteristics could not be obtained without a very great sacrifice of efficiency. Because of the large force factors obtaining in the receivers of the invention, the desired negative mass effect is obtained without substantial loss of efficiency.

In the modified form of the invention shown in Fig. 7, the damping elements take the schematic form shown in Fig. 11, which differs from that of Fig. 8 by the addition of a stiffness S_{01} , directly in series with the mass and resistance. This added stiffness is that of the enclosed chamber 47 behind the perforated plate 48. The effect of the closed chamber is to diminish the volume and velocity of the air leakage through the perforations, and, hence, to reduce the rate of energy dissipation. To compensate this reduction, the resistance of the damping element must be increased when the closed chamber is used. Another effect is to add a stiffness restraint to the diaphragm equal to the stiffness of the total enclosed space behind the diaphragm. In Fig. 11, S_{01} is the stiffness of the enclosed chamber 47, M_1' and R_1' are, respectively, the mass and resistance of the apertures in damping plate 48, and S_1' is the stiffness of air chamber between the diaphragm and frame 45.

By means of a transformation theorem described by O. J. Zobel, Bell System Technical Journal, January 1923, Theory and design of uniform and composite electric wave filters, Appendix III, Transformations A and B, it may be shown that this modified damping can, by suitably proportioning the elements, be made the full equivalent of the combination M_1 , R_1 , S_1 , of Fig. 8, together with a stiffness added in series externally to the group. The equivalent schematic is shown in Fig. 12 in which S_4 represents the added stiffness.

The curves of Fig. 10 represent the characteristics of an experimental device of the type shown in Fig. 7 for which the mechanical and acoustic constants had the following values:

$R=125$ ohms
 $n=700$ turns
 $r_1=18.9$ ohms, $L_1=.00683$ henry
 $r_2=179$ ohms, $L_2=.00957$ henry
 $R_0=300$ mechanical ohms
 $M_0=.60$ gram
 $S_0=24 \times 10^6$ dynes per cm.
 $S_1'=49 \times 10^6$ dynes per cm.
 $S_{01}=27 \times 10^6$ dynes per cm.
 $M_1'=.58$ gram
 $R_1'=5600$ mechanical ohms
 $S_2=19 \times 10^6$ dynes per cm.
 $S_3=4.6 \times 10^6$ dynes per cm.
 $M_3=.088$ gram
 $R_3=130$ mechanical ohms
 $G=26 \times 10^6$ c. g. s.

The corresponding constants of the equivalent damping system, Fig. 12, are:

$R_1=2330$ mechanical ohms
 $M_1=.241$ gram
 $S_1=31.6 \times 10^6$ dynes per cm.
 $S_4=17.4 \times 10^6$ dynes per cm.

The mass reactance of the diaphragm is represented by straight line D and the effective mass by curve E, the difference between the two being the negative mass reactance indicated by curve C. Dotted straight line F represents the average value of the effective mass reactance. The reduction of the diaphragm mass in this instance is substantially 60 per cent. The total reactance of the system which is the resultant of the effective mass reactance and the combined reactances of the diaphragm stiffness S_0 , rear chamber stiffness S_4 , and front chamber stiffness S_2 and S_3 , is represented by curve G. The total reactance is zero at 2150 C. P. S., corresponding to the effective resonance frequency of the diaphragm.

From the constants given above, the various significant resonance frequencies of the system may be determined. The values are as follows: The diaphragm by itself, that is, in the absence of acoustic stiffness restraints has a resonance frequency of 1000 C. P. S. With the addition of the acoustic restraints represented by stiffness S_4 and the parallel connection of S_2 and S_3 , the diaphragm resonance is increased to 1400 C. P. S. The acoustic damping system comprising resistance R_1 , stiffness S_1 and mass M_1 is proportioned so that M_1 and S_1 resonate at about 1850 C. P. S. The load system represented by ear cavity stiffness S_3 , mass M_3 , and front chamber stiffness S_2 is resonant at about 2700 C. P. S. Further, as shown by curve G of Fig. 10, the final effective resonance of the diaphragm occurs at a frequency in the neighborhood of about 2150 C. P. S., the increase from 1400 C. P. S. representing the effect of the mass reduction due to the combined electrical and acoustical damping.

To secure uniformity of response I have found it desirable to maintain certain relationships among these resonance frequencies. Preferably, the three resonance frequencies of the diaphragm and the ear cavity resonance should form approximately a geometric series with a ratio of the terms of about 1.4:1 or 1.5:1. Under this condition, the extension of the response range above the resonance frequency of the diaphragm itself is contributed in about equal parts by the acoustic stiffness, the reduction of mass due to damping, and the resonance of the ear cavity. The frequencies 1000, 1400, 2150 and 2700 C. P. S. mentioned, correspond quite closely to the series, 1000:1400:1960:2750. In addition, the resonance frequency of the rear damping system should be approximately equal to or greater than the final effective resonance of the diaphragm, in order that the mass reduction may be effective over substantially the whole operating frequency range. In the foregoing example, the values are 1850 C. P. S. and about 2150 C. P. S., respectively, which is satisfactorily close.

In the device according to Figs. 1 to 6, the absence of the acoustic stiffness S_4 tends to reduce the effective resonance frequency of the diaphragm. However, since the mechanical stiffness of the diaphragm varies as the cube of the thickness, the reduction may be compensated by a slight increase in the diaphragm thickness, without noticeable sacrifice of the figure of merit.

A typical response characteristic for the device of Fig. 7 is shown in Fig. 13, the ordinates of which represent the acoustic pressure in the ear cavity in decibels above the standard threshold value of one bar per watt of input power. The diaphragm resonance and the ear cavity resonance appear as slight undulations at 2150 C. P. S. and 2800 C. P. S. At low frequencies, the full line curve represents the response in a completely closed ear cavity corresponding to the reference conditions previously described. The dotted curve shows the effect of normal air leakage between the receiver cap and the ear. At a frequency of 300 C. P. S. the loss of sensitivity is 5 decibels and increases rapidly with decreasing frequency. Since frequencies below 300 C. P. S. are of relatively small importance in speech transmission, the limitation of the response range at the lower range is not of consequence. At higher frequencies the effect of normal air leakage is negligible.

As heretofore stated, a single bar magnet such as 27, may be used instead of two of such magnets as shown in Fig. 6. In case a single magnet is employed, it may be made of an alloy comprising iron, cobalt and molybdenum in the approximate proportions 72:12:16 and have a cross-sectional area of about one-sixteenth of a square inch and a length of about 1.25 inches.

Reference is made to Patent 2,231,084 granted Feb. 11, 1941, on an application Serial No. 161,936, filed September 1, 1937, a division of the application Serial No. 93,792, filed August 1, 1936, wherein certain features of the devices described hereinabove are claimed.

What is claimed is:

1. In a sound translating device, a moving system comprising a vibratory diaphragm and having a predetermined response characteristic over an operating frequency range when arranged for substantially free vibration, means defining a first chamber adjacent the inner side of said diaphragm having a passage communicating therewith, the dimensions of said passage being so proportioned that said first chamber acts substantially entirely as a damping chamber effective substantially to decrease the response of said moving system at frequencies within a band of frequencies extending toward the low frequency end of said range, and means defining a second chamber adjacent the outer side of said diaphragm having a passage communicating therewith, the dimensions of said last-mentioned passage being so proportioned that said second chamber acts substantially entirely as a resonating chamber effective substantially to increase the response of said moving system at frequencies within a band of frequencies extending toward the high frequency end of said range.

2. In a sound translating device, a housing, a diaphragm mounted within said housing, said diaphragm having a predetermined response characteristic over an operating frequency range when mounted within said housing for substantially free vibration, said diaphragm having a natural frequency of vibration such that said response characteristic peaks at frequencies within the low frequency end of said range, means defining a first chamber adjacent the inner side of said diaphragm having a passage communicating therewith, the dimensions of said passage being so proportioned that said first chamber acts substantially entirely as a damping chamber effective to remove said peak from the response

characteristic of said diaphragm and substantially to decrease the response of said diaphragm at frequencies within a band of frequencies extending from a frequency of the order of 1500 cycles per second toward the low frequency end of said range, means defining a second chamber adjacent the outer side of said diaphragm having a passage communicating therewith, the dimensions of said last-mentioned passage being so proportioned that said second chamber acts substantially entirely as a resonating chamber effective substantially to increase the response of said diaphragm at frequencies within a band of frequencies extending from a frequency of the order of 2000 cycles per second toward the high frequency end of said range.

3. In combination in a telephone receiver, a diaphragm, and impedance means cooperatively associated with said diaphragm for substantially reducing the effect of the mass reactance of said diaphragm in a substantially uniform proportion at all frequencies in the range to be reproduced.

4. In combination in a telephone receiver, a diaphragm having a substantial mass effect over the frequency range to be reproduced, and means introducing a substantially uniform negative mass effect throughout said range to reduce the effective mass of the diaphragm in the order of 50 per cent.

5. A telephone receiver comprising a diaphragm having a natural period in the frequency range to be reproduced, and acoustic means associated therewith, said means possessing the property of introducing resistance to flatten out the resonance peak of the diaphragm vibrations and negative mass reactance to reduce the effect of the mass reactance of the diaphragm substantially uniformly throughout a range of at least 1000 cycles above said natural period.

6. A telephone receiver comprising a frame member containing an air chamber and an aperture connecting with said air chamber, acoustic damping means across said aperture, a magnetic diaphragm on said support and forming a shallow air chamber with said frame, said first and second chambers being completely closed except for connection to each other through said aperture, and means for exerting a constant and a superimposed alternating magnetic force on said diaphragm, said diaphragm being maintained in position by magnetic forces only.

7. A telephone receiver comprising a diaphragm having a positive mass reactance increasing substantially linearly with frequency, and means coupled to said diaphragm defining a negative reactance increasing substantially linearly with frequency.

8. A sound translating device comprising a diaphragm having a natural period of vibration in the frequency range to be translated, electromagnetic signal translating means cooperatively associated with said diaphragm, means defining an acoustic damping system adjacent one surface of said diaphragm effective to flatten out the resonance peak of the diaphragm vibrations, said system comprising resistance, mass and stiffness, the resistance being of the order of the square root of the product of the mass and stiffness, and means defining an acoustic resonating system adjacent the other surface of said diaphragm effective to increase the response of said diaphragm throughout a band of high frequencies in said range, said resonating system having substantially negligible resistance.

9. A sound translating device comprising a dia-

phragm having a natural period of vibration of the order of 1,000 cycles per second, electromagnetic signal translating means cooperatively associated with said diaphragm, means defining an acoustic network adjacent one surface of said diaphragm and including resistance sufficient to substantially suppress the resonance peak of the diaphragm vibrations, said network including also mass and stiffness resonant at of the order of 2,000 cycles per second, said resistance, mass 10 and stiffness being proportioned so that the ef-

fective resistance of said network is greater than the effective reactance of said network throughout a range of frequencies extending from below 1,000 cycles per second to of the order of 2,000 cycles per second, and means defining a second acoustic network adjacent the other surface of said diaphragm, said second network having substantially negligible resistance and being resonant at the order of 2,700 cycles per second.

EDWARD E. MOTT.