June 10, 1930. R. V. L. HARTLEY 1,762,981

ACOUSTIC DEVICE

Filed June 6, 1928

FIG. 1.

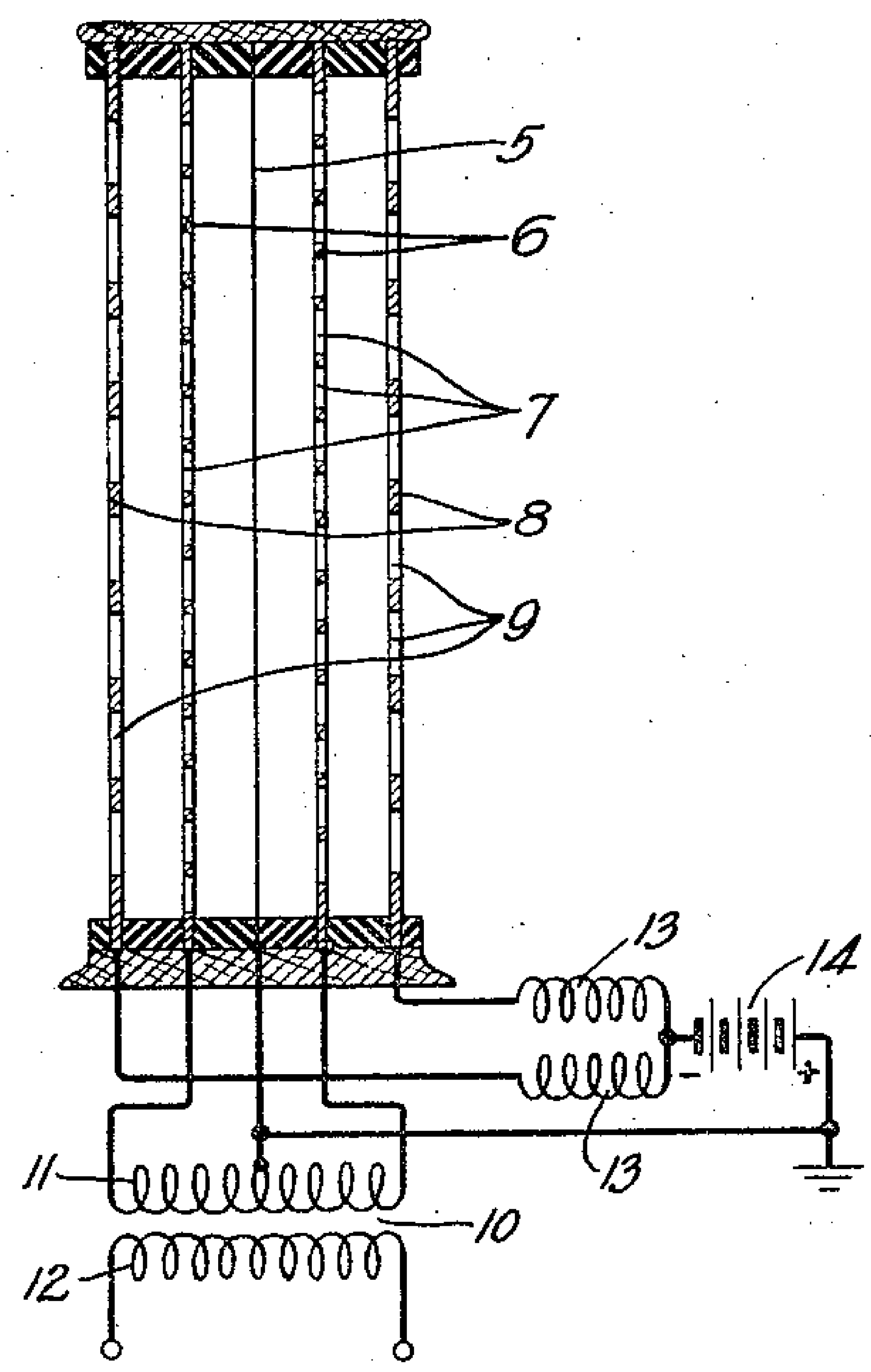


FIG. 2.

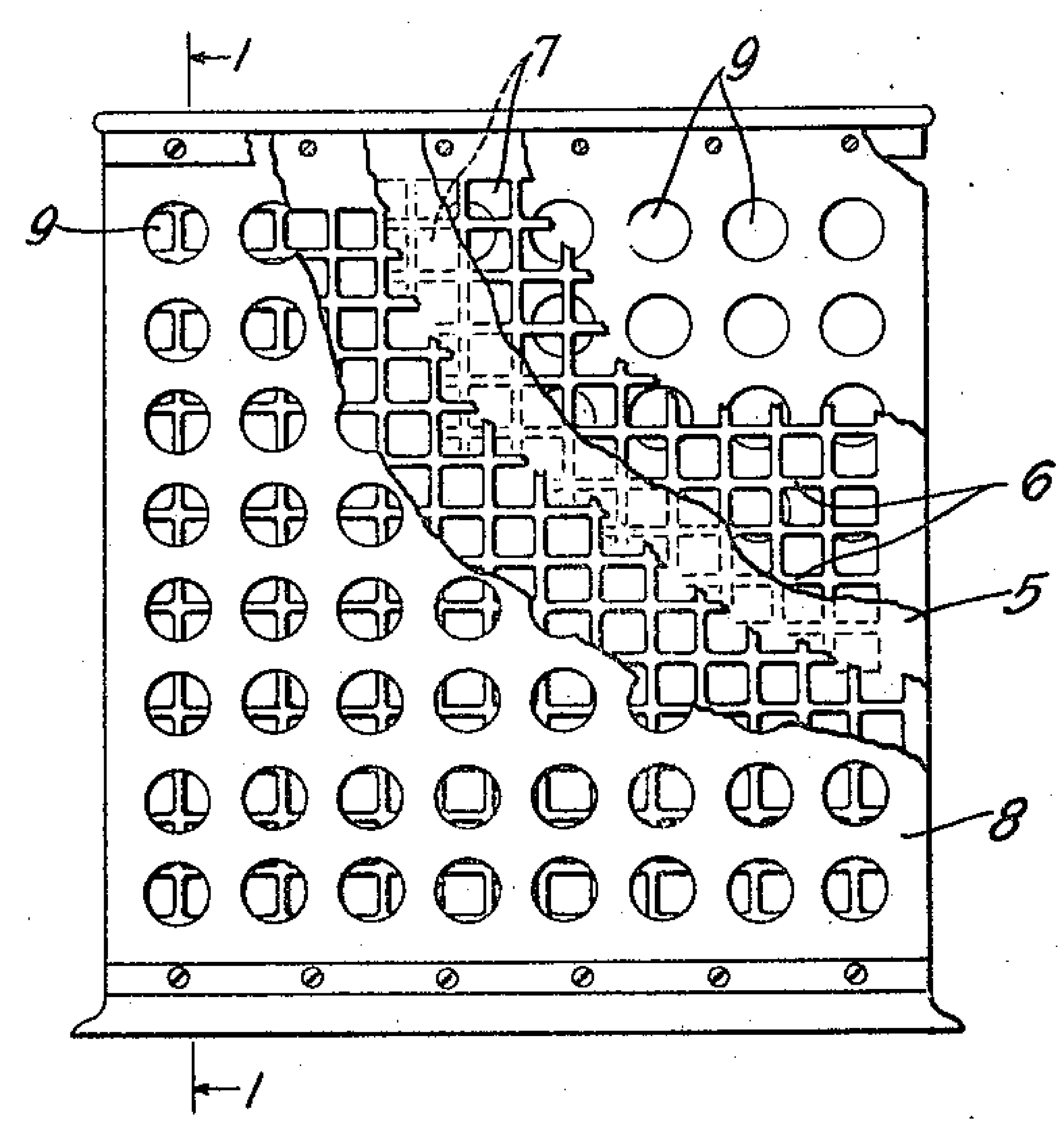
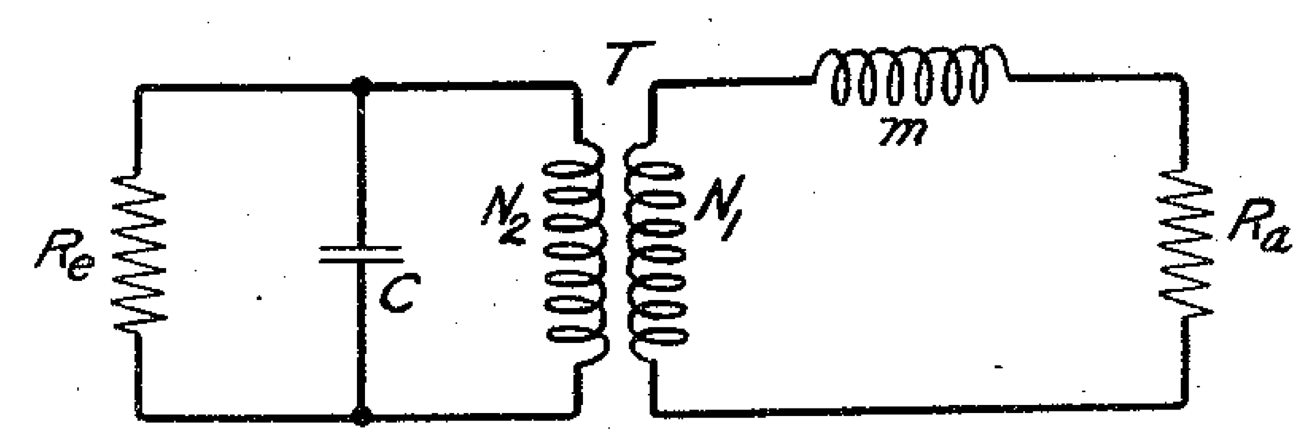


FIG. 3.



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UNITED STATES PATENT OFFICE

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ACOUSTIC DEVICE

Application filed June 6, 1928. Serial No. 283,200.

This invention relates to acoustic devices and particularly to an electrostatically operated device.

An object of this invention is to radiate sound energy with substantially uniform efficiency over at least a large portion of the frequency range employed in speech and music.

Another object of this invention is to change electrical vibrations into sound vibrations or sound vibrations into electrical vibrations through the use of a charged diaphragm suspended in an electrostatic field.

Heretofore attempts have been made to use thin electrically conductive diaphragms having negligible mass and elasticity loosely supported in electrostatic fields between metallic members which exert attractive forces on all portions of the diaphragm surfaces. This has been done by placing a charge of one polarity on the diaphragm and charges of opposite polarity to that of the diaphragm on metallic members on either side of the diaphragm. An objection to this method is that as the diaphragm is held at rest midway between the metallic members by equal attractive forces on its either side if the diaphragm is caused to approach one of the metallic members by an external force the attractive force of that member towards the diaphragm increases and the diaphragm approaches still nearer the one member and will come to rest in a position nearer the one member than the other. Obviously a diaphragm supported between attractive forces in this manner can not be said to be in stable equilibrium. To prevent the diaphragm in such a device from being in unstable equilibrium, external restoring forces are required which necessitate the use of a stronger and heavier diaphragm.

This invention overcomes the difficulty experienced in the method outlined above by placing the electrically charged diaphragm between metallic screens which are electrically charged with the same polarity as the diaphragm. The diaphragm is then held in stable equilibrium between the screens under electrostatic forces of repulsion. If the diaphragm through some outside influence is caused to approach near one of the screens the repulsive force between the diaphragm and the one screen will increase and on the removal of the external force the diaphragm will be forced by the repulsive force of the nearer screen to the mid position. It is thus seen that the diaphragm according to this invention is held in stable equilibrium under the restoring forces of electrostatic repulsion, and since no external restoring forces are used, a very thin and light foil may be used for the diaphragm.

In one embodiment of this invention a thin foil diaphragm is loosely supported between two grid screens, the grid screens being so constructed with a large number of perforations that although they extend along the entire surface of the diaphragm a large portion of the diaphragm is not covered by the screens. The grid screens are supported between two plate screens which are perforated to permit the passage of sound waves.

If, for example, the outer or plate screens are given a negative charge, the inner or grid screens are charged positively. However, due to the incomplete shielding of the foil by the inner screens it also takes up a positive charge and so is repelled by both of the inner screens in a manner similar to the repulsion of the leaf of an electroscope. The foil is therefore in stable equilibrium at the mid position. The restoring force tending to hold it in that position depends upon the location of the screens, the sizes of their openings and the polarizing battery. For use at low frequencies, particularly, this restoring force should be made as small as possible without sacrificing stability.

When an alternating electromotive force is applied between the two inner screens one attracts the foil and the other repels, thus setting it in motion at the frequency of the electromotive force. Similarly, motion given to the foil by the air sets up an electromotive force between the two inner screens. High impedances may be inserted in the leads to the two outer screens and to the foil to prevent induced currents flowing between them under the action of the voltage applied between the inner screens. To make the force on the foil more uniform the openings in the screens on the two sides should preferably be offset with respect to each other.

While the principle of operation could probably be utilized with screens on only one side of the foil, the restoring forces then being the repulsion of the inner screen and attraction of the outer, this arrangement has several disadvantages as compared with the double screen. There would be no protection against the rupture of the foil by excessive air pressure tending to move it away from the screens. The restoring force would not be symmetrical about the position of equilibrium, which would tend to result in distortion. The double screen arrangement is also analogous to the push-pull amplifier in its elimination of even orders of modulation.

By having the diaphragm, according to this invention, under electrostatic forces of repulsion, no external restoring forces are required to hold the diaphragm at its mid position between the polarizing plates. No tension is, therefore, placed on the diaphragm and it can be made of very light and thin material such as foil, having negligible mass and elasticity. By employing a diaphragm having negligible mass and elasticity an electrical transmitter or receiver having high efficiency and uniform response over a wide range of frequencies is obtained.

An electrostatic transmitter arranged according to this invention has a diaphragm so free to move that it will follow faithfully the wave form of the sound giving a velocity response rather than a pressure response, the pressure of the wave front passing through the foil instead of being reflected back.

Referring to the drawings, Fig. 1 shows an acoustic device constructed according to this invention and is a sectional view along the lines 1—1 of Fig. 2, showing the relative arrangement of the diaphragm, grids and plates together with the energy supply circuit.

Fig. 2 is an elevation view of a transmitter or receiver, constructed according to this invention, with portions removed to show the details of construction.

Fig. 3 is the equivalent electrical circuit of the transmitter or receiver showing the acoustic load connected to the electrical load.

The foil diaphragm 5 is loosely supported between and equidistant from the grids 6. The grid members 6 are so arranged with respect to each other on either side of the diaphragm 5 that their apertures 7 are offset with respect to each other. This gives a more uniform distribution of the forces exerted by the grids on the diaphragm. Plates 8 are arranged on either side of and equidistant from grids 6. Plates 8 are provided with apertures 9 which permit the passsage of air to and from the diaphragm 5. Transformer 10 serves as an input transformer to conduct the alternating voltage to the grid 6 when the device is used as a receiver and serves as an output transformer when the device is used as a transmitter. The ends of winding 11 of transformer 10 are connected each to one of the grids 6. The mid-point of winding 11 is connected to the diaphragm 5 and to the positive side of polarizing battery 14. The negative side of battery 14 is connected through choke coils 13 to the two plates 8. The two coils 13 are high impedances which serve to prevent induced currents from flowing between the plates and between the plates and the diaphragm under the action of the voltage applied between the grids. The diaphragm is shown by Fig. 1 to be grounded. It is clear, however, that certain other parts of the structure may be placed at ground potential without interfering with the operation of the device.

The battery 14 places a negative charge on the plates 8. This, by the well known condenser action, causes a positive charge to be placed on the grids 6. The grids 6 do not completely shield the diaphragm 5 from the plate 8 so that the diaphragm 5 also takes a positive charge. Since the diaphragm 5 and the grids 6 have electrical charges of the same polarity the grids 6 both repel the diaphragm 5 and since the grids are arranged on either side of the diaphragm it is held in stable equilibrium at its mid position between the grids. An alternating electromotive force applied to the terminals of winding 12 of transformer 10 causes, since the grids are connected to the outer ends of winding 11 and the diaphragm is connected to the mid-point of winding 11, the charge on one grid to be increased while the charge on the other grid is simultaneously decreased. This causes one grid to attract and the other grid to repel the diaphragm thus setting it in motion at the frequency of the electromotive force. In the same way motion given to the diaphragm 5 by sound waves sets up an electromotive force between the two grids 6.

Fig. 3 shows the equivalent circuit of this invention used as an electrostatic transmitter or receiver.

R_e=the electrical load resistance.

C=the capacity of the system to an alternating voltage applied to the grids.

T=the equivalent transformer connecting the acoustic load to the electrical load.

N_2=the equivalent electrical winding of the transformer T.

N_1=the equivalent acoustic winding of the transformer T.

m=the mass of the diaphragm.

R_a=the acoustic load resistance.

The ratio $\frac{N_1}{N_2}$ is the ratio of the turns of the windings of the equivalent transformer T and is equal to the mechanical force divided by the voltage at the grids.

A theoretical investigation of the structure may be made by writing the electrostatic energy of the system in terms of the potential coefficients and the charges on the elements. By assuming that the outside plates are effectively uniform conducting surfaces from an electrostatic standpoint, the expression for the energy may be reduced to a function of the dimensions of the structure, the charges, and two potential coefficients, which are defined as the potential per unit charge on each grid when the plate charges, are zero. By expanding the coefficients by Taylor's theorem about the central equilibrium position of the membrane and finding the mechanical force in the usual way by differentiation, an expression for the force is obtained in terms of one potential coefficient and its derivatives.

Clerk Maxwell in Vol. 1 of Electricity and Magnetism published by MacMillian Company, London, has given a treatment of the electric field due to a charged grid of wires between two conducting plates. Following Maxwell's notation, the radius of the wires may be denoted by c, their distance apart by a, the distance from the grid to the moving membrane by b_1 and the distance from the grid to the stationary plate by b_2. The potential coefficient giving the potential on the grid due to unit charge on that grid is denoted by p_{11}.

It is shown that to make the second harmonic distortion low, it is desirable to make the second derivative of p_{11} with respect to the displacement equal to zero at the equilibrium point. This condition will also make the electrostatic elasticity zero. The requirement to fulfill this condition is

$$\log\frac{a}{\pi c}=\frac{2\pi b_2}{a} \quad (1)$$

Maxwell's first treatment of the subject of the charged grid required b_2 to be large compared with a. He later gave a "Method of Approximation" in the form of a series which gives good results when b_1 and b_2 are of the same size or somewhat smaller than a. In order to express the results of this investigation in a reasonably simple form, it will be assumed that

$$e^{\frac{-4\pi b}{a}}\ll 1$$

where the b may be either b_1 or b_2. This relation holds for approximate purposes when

$$4b>a \quad (2)$$

Combining this relation with Equation (1)

$$4b>a>15c \quad (3)$$

Equation (1) then gives the condition for minimum distortion and electrostatic elasticity and Equation (3) gives the conditions under which the approximations hold.

Representing the alternating charge on the grids by q and the steady applied voltage on the plates by V, the expression for the force on the membrane may be written

$$F=\frac{2V_q}{b_2+b_1\frac{(2b_2-.11a)}{(b_2-.11a)}}$$

If $b_1=b_2=b$, the expression reduces to

$$F=\frac{\left(1-.11\frac{a}{b}\right)V_q}{\left(\frac{3}{2}-.11\frac{a}{b}\right)b} \quad (4)$$

The capacity of the system to the alternating charge q is

$$C=\frac{A}{\left(8\pi b\,(2-.11\frac{a}{b}\right)} \quad (5)$$

where A is the area of the membrane. If v be the alternating voltage applied between the two grids then

$$\frac{F}{v}=K=\frac{AV}{8\pi b^2}\,\frac{\left(1-.11\frac{a}{b}\right)}{\left(\frac{3}{2}-.11\frac{a}{b}\right)\left(2-.11\frac{a}{b}\right)} \quad (6)$$

K is defined by (6). It is represented in the equivalent circuit by the turnsratio $\frac{N_1}{N_2}$ of the transformer T.

In order that the electrostatic element be a highly efficient device, two things are necessary; first that Z, the mechanical impedance per unit area of the diaphragm with its air load, is primarily the radiation resistance to the air, and second that the reactance of the capacity C be large compared to the impedance $\frac{ZA}{K^2}$. If the membrane be made of .0005″ aluminum, its mass reactance will be only about twice the radiation resistance of the air at 5,000 cycles which would not introduce a large loss. The second requirement is much more serious, however. With practicable voltages and separations, the capacity C will probably always predominate, which, for a good frequency response characteristic, would lead to an inefficient arrangement.

In order to obviate the last difficulty a "negative capacity" as secured by one of the various vacuum tube circuits may be connected across the terminals of the structure. A relatively small corrective capacity would be required.

In considering the arrangement as a transmitter, b the distance between grid and plate is taken as equal to the distance between grid and diaphragm, a the separation between the wires of the grid and V the steady voltage applied to the plates. The choice of the values of a and b are restricted and fix the value of

c, the radius of the grid wires, in the manner previously discussed.

The insertion of numerical values in the formulas will show that the motional impedance of the electrical elements on the mechanical side will be negligible for practicable value of polarizing voltage. The diaphragm may then be considered simply as a membrane suspended in the sound path. Let the velocity of the membrane be $\dot{x}$, the current then at the left of the transformer in Fig. 3 of the drawing is given by

$$i=K\dot{x}=\frac{AV\dot{x}}{8\pi b^2}\frac{\left(1-.11\frac{a}{b}\right)}{\left(\frac{3}{2}-.11\frac{a}{b}\right)\left(2-.11\frac{a}{b}\right)}$$

If the resistance R_e is made equal to the reactance of the condenser C at some frequency f_0, then below this frequency the current in the resistance R_e will be substantially the same as i. We have then that

$$R_e=\frac{4b\left(2-.11\frac{a}{b}\right)}{Af_0}$$

and the voltage across the resistance R_e due to the velocity $\dot{x}$ of the membrane is

$$v=\frac{V\dot{x}}{2\pi f_0 b}\frac{\left(1-.11\frac{a}{b}\right)}{\left(\frac{3}{2}-.11\frac{a}{b}\right)}.$$

Assuming values for the consonants of

$f_0=5000$ cycles
$a=.25$ cms.$=.0985''$
$b=.10$ cms.$=.0394''$
$c=.0065$ cms.$=.0026''$

gives $v=\frac{V\dot{x}}{5310}$.

If the membrane is sufficiently light to move freely in the sound field without introducing distortion, $\dot{x}=\frac{p}{41}$ where p is the pressure of the sound wave, and $\frac{v\times10^3}{p}=\frac{V}{218}$. The quantity

$$\frac{v\times10^3}{p}$$

for a condenser transmitter is approximately equal to 4, so that for equal efficiency, the device under consideration would require a polarizing voltage of 872 volts. The efficiency would be higher if the elements of the structure were placed closer together, but there are, of course, practical difficulties in the construction of such a device. With the dimensions assumed above, a grid of 5.2 mil wire separated from the plate and membrane by 40 mils is thought to be reasonable.

It will be noted that the area does not enter into the expression for voltage sensitivity. It does, however, determine the value of the resistance R_e, the proper value may readily be found to be $R_e=\frac{124}{A}$ megohms and the capacity $C=\frac{A}{3.90}$ micro-microfarads. For an area of 100 square centimeters, the required resistance would be 1.24 megohms and using this value, the loss due to the capacity shunt would be approximately 3 TU at 5,000 cycles.

Although the device as illustrated is shown as rectangular in shape, it will be understood that the plates and diaphragm may be of other shapes, circular, for example, and that said plates and diaphragm may be held in spaced relationship in any desired manner.

What is claimed is:

An acoustic device comprising a metallic diaphragm, a perforated plate member on each side of said diaphragm, a perforated grid member between each of said plate members and said diaphragm, a direct current source connected at its one pole to said diaphragm and at its opposite pole to said plate members, and means for applying a varying electrical force to said grid members, the perforations in said grid and plate members being offset with respect to each other whereby an electrical charge of one polarity on said plate members may cause a charge of opposite polarity on said grids and through the perforations in said grid member on said diaphragm.

In witness whereof, I hereunto subscribe my name this 5th day of June, 1928.

RALPH V. L. HARTLEY.