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COMPLETE SPECIFICATION.

Improvements relating to Electrostatic Loudspeakers.

We, FERRANTI LIMITED, a Company registered under the laws of Great Britain, of Hollinwood, in the County of Lancaster, and PETER JAMES WALKER, a British Subject, c/o The Acoustical Manufacturing Co. Ltd., Huntingdon, County of Huntingdon, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to electrostatic loudspeakers, by which term is meant a loudspeaker which depends for its action on the force of electrostatic attraction between a movable or flexible diaphragm electrode and a rigid plate electrode secured closely parallel to it.

To reduce non-linear distortion it is usual to locate the diaphragm between two such fixed plate electrodes, one at least of which may be perforated or may be of lattice construction to allow motion of air through it.

To increase the sensitivity and avoid a frequency-doubling effect caused by attraction taking place on both halves of the signal waveform it is also usual to apply a steady polarizing voltage so as to maintain a biasing potential between the diaphragm on the one hand and each of the two fixed plates.

The polarizing and audio-frequency signal voltages may be applied in either of two ways:—

(1) The positive terminal of the polarizing source 10 (see Fig. 1 of the accompanying drawings) is connected to one fixed plate 11 and the negative terminal to the other fixed plate 12, the signal voltage from a source 13 being applied between the diaphragm 14 and the point 15 of mid-potential of polarizing source 10; or

(2) The signal voltage from source 13 is applied by way of a transformer 16 (see Fig. 2) to the fixed plates 11 and 12 and the polarizing voltage 10 is applied between the diaphragm 14 and a centre tap 17 on the transformer secondary 18.

For good sensitivity the polarizing voltage should be high, and difficulty has been experienced with known arrangements of the above-described kinds through the tendency of a spark discharge to occur between the diaphragm and the plates, with consequent audible distortion.

With arrangement (2), the damaging effect of such a discharge may be reduced by inserting a resistance 19 (see Fig. 2) of high value in the connection between the polarizing source 10 and the diaphragm 14; this resistance has the effect of preventing the full polarizing voltage from being applied continuously once a spark current develops but does not prevent a spark from occurring. With loudspeakers of all but the smallest size, however, this arrangement is not satisfactory because the capacitive charge stored in the loudspeaker is considerable and sufficient in itself to cause damage if a spark should occur.

With arrangement (1), the insertion of resistance large enough to prevent sparking is not practicable because all connections carry the signal currents and the presence of such a resistance would increase the time-constant of the circuit too much.

An object of the present invention is to provide an electrostatic loudspeaker with improved linearity of response.

Another object is to provide an electrostatic loudspeaker which allows the application of a high polarizing potential to the diaphragm electrode without the occurrence in operation of audible distortion due to sparking between the diaphragm electrode and the fixed plate electrodes.

As electrostatic loudspeaker units in accordance with the invention have physical characteristics which make them suitable for combination in arrays, another object is to provide an array of such units.

A further object is to provide a loudspeaker stage (by which is meant the combination of a loudspeaker unit with its source of polarizing potential) including at least one electrostatic loudspeaker unit having improved linearity, which stage allows of the application of a high polarizing potential at the diaphragm electrode of the unit without the occurrence in operation of audible distortion due to sparking between the diaphragm electrode and the fixed plate electrodes.

In accordance with the present invention an electrostatic loudspeaker unit comprises two rigid plate electrodes in close parallel relationship insulated from one another and secured between them a diaphragm electrode of flexible material the electrical resistivity of the surface of which lies within a range of the order of 2×10^{9} to 1×10^{12} ohms per unit square, there being provided at least one polarizing electrode in contact with the diaphragm.

Also in accordance with the invention there is provided a loudspeaker stage including at least one electrostatic loudspeaker unit as set forth in the preceding paragraph, driving means for applying an audio-frequency signal to the plate electrodes of the unit, and polarizing means connected to said polarizing electrode, or to each polarizing electrode, as the case may be, for maintaining the diaphragm electrode at a high uniform electrostatic charge with respect to the plate electrodes.

In the accompanying drawings:—

Figures 1 and 2 are schematic diagrams of known arrangements of electrostatic loudspeakers;

Figure 3 shows an electrostatic loudspeaker stage in accordance with one embodiment of the invention, in part as a schematic diagram and in part as a section through a loudspeaker unit, the thickness and spacing of the components being considerably exaggerated for clarity;

Figures 4 and 5 show to an enlarged scale parts of Figure 3 but to a modified construction;

Figures 6 to 8 show sections through parts of loudspeaker units in accordance with other embodiments, the thickness and spacing of the components being again exaggerated;

Figures 9 and 10 are sectional views of arrays of loudspeaker units in accordance with the invention;

Figure 11 is a view in perspective of another array, partly in expanded form;

Figures 12 and 13 are sectional views of two other arrays;

Figure 14 is a sectional view through another embodiment; and

Figure 15 is a schematic diagram of a further embodiment.

In carrying out the invention in accordance with one form by way of example, an electrostatic loudspeaker includes a number of loudspeaker units each of which comprises a flexible diaphragm 21 (see Fig. 3) of resistive sheet material such as nylon, the electrical resistance of which satisfies certain requirements which will be specified later. The sheet is sandwiched between two closely-parallel plates 22 and 23 which can be of metal or conductive material or conductively coated material or of conducting material with an insulating sheath depending on constructional and operating requirements. The size of the units is determined either by constructional requirements or by acoustic loading requirements of that particular radiating area. By way of example a rectangular unit of 6″ × 6″ size might form part of a larger area of similar units, or on its own would be suitable for radiating medium and high audio frequencies. Plates 22 and 23 are thick enough to be rigid and both of them are perforated, as depicted at 24, to provide apertures for the emission of sound waves and prevent "cushioning" of the vibration. The diaphragm is secured in tension by being clamped throughout its periphery between peripheral polarizing electrodes in the form of metal strips or foils 25. These strips are themselves clamped between plates 22 and 23, strips 26 of polythene or other convenient insulating material being interposed between strips 25 and the plates to insulate the plates from one another and the diaphragm from the plates.

Conductive strips 25 should extend inwards, as shown in the drawing, beyond insulation strips 26 to prevent any leakage between the diaphragm and the plates which would cause a voltage drop across a free part of the diaphragm, for such a voltage drop would prevent the full polarizing voltage from appearing on the diaphragm and would render the performance of the loudspeaker unit unpredictable. The spacing between the diaphragm and the plate is sufficient to allow free vibration of the diaphragm at the maximum amplitude required. Suitable terminals 22^1 and 23^1 are provided in electrical connection with the plates and a further terminal 21^1 connected to the conductive strips 25 and hence to the diaphragm. The units may be assembled side by side with the outer surfaces of the perforated plates coplanar. Other possible assemblies will also be discussed later.

The two plate terminals 22^1 and 23^1 of each unit are connected respectively to the ends of the secondary winding 28 of a signal output transformer 29 common to all the units the primary winding 30 of which is energized by the final stage 31 of signal amplification. Each unit is polarized by connecting a source 32 of high tension of several hundred volts per centimetre of spacing between the diaphragm terminal 21^1 and a centre tap 33 on transformer secondary 28; as a safety precaution the more accessible of the two plates, plate 23, say, is connected to earth. Alternatively, where more convenient, the polarizing supply may be returned to either end of the transformer secondary 28 instead of to the centre tap 33.

The electrical resistance of diaphragm 21 is determined by three considerations.

In the first place the surface resistance must be high enough to maintain sufficiently constant the total charge on both sides of the diaphragm of an elemental area despite the variation of the capacitance of this elemental area due to the audio-frequency vibration of the diaphragm.

By "sufficiently constant" is meant constant enough to render distortion inappreciable to the trained ear. Such constancy of charge reduces non-linearity due to the quadratic nature of the forces which are involved if the diaphragm potential is fixed. Owing to the fact that in any practical loudspeaker the diaphragm does not operate as a rigid piston because of the necessity for supporting members and because acoustic impedances are not always uniformly distributed over its area, the same degree of improvement is not obtainable by the insertion of resistance external to a conducting diaphragm.

Secondly, the resistance must also be high enough to prevent audible distortion due to sparking in normal operation, so that if a spark should tend to occur between a small area of the diaphragm and one of the plates, the discharge current flowing in the areas of the diaphragm adjacent to the discharging area causes the potential of the discharging area to be reduced below the value required to maintain the discharge, hence only a very small charge is dissipated before the voltage becomes thus reduced and distortion due to the spark is accordingly rendered inaudible.

Thirdly, the upper limit to the value of the resistance is determined by the necessity of allowing the polarizing charge to spread uniformly across the diaphragm from the polarizing electrode or electrodes within a reasonably short time after switching on the supply.

A range of surface resistivities of the order of 2×10^9 to 1×10^{12} ohms per unit square is found to satisfy the above requirements.

A suitable material for the diaphragm is nylon, the surface of which, owing to its affinity for moisture, has the above stated resistance range over the relative humidity range 95% to 38%.

Electrostatic loudspeakers have been proposed which have diaphragms of polythene, cellulose nitrate, or other plastic materials. But as these materials have an almost negligible affinity for moisture their surface resistivities remain too high (even at the maximum value of humidity likely to be encountered) to allow of a uniform spread of the polarizing charge within a reasonable time after switching on the supply.

The upper limit to the value of the polarizing potential is determined by the onset of ionization in the spaces between the diaphragm and the plates; which will occur at approximately 70 volts per mil of the space between either plate and the diaphragm.

It will be noticed that the energizing system is that of arrangement (2) (Fig. 2), previously mentioned, that is, the AF currents which energize each unit, flow only in the outer electrodes; a diaphragm resistance that is high enough to satisfy the requirements indicated above is far too high for the diaphragm to take the AF currents—in accordance with arrangement (1)—without considerable attenuation and distortion.

The use of the conductive strips 25 is rendered advisable because of the high resistivity of the diaphragm. If the polarizing potential were to be applied at a point or at a few points on the periphery of the diaphragm and the intervening portions of the periphery where separated from the plate electrodes merely by the insulation strips 26, the leakage through the latter from the diaphragm would prevent the diaphragm from being uniformly charged. The insertion of conductive strips between the diaphragm and the insulating supports removes these leakage paths from the high-resistance diaphragm itself and transfers the leakage directly on to the power supply where it need cause no embarrassment.

Where the diaphragm area is small compared with the wavelength radiated, the frequency response may be equalized by mechanically loading parts of the diaphragm either by thickening or by adding button-shaped portions of other material, in each case as depicted at 21^1 in Fig. 4. At the higher frequencies these loaded parts remain relatively stationary and vibrational displacement occurs mainly in the intermediate areas of low mass, from which areas effective treble radiation takes place. At the lower frequencies the diaphragm vibrates as a whole, the increased mass lowering the bass resonance frequency.

In the construction of Fig. 3 there is some wasteful capacitance in areas not contributing to sound output. These areas are constituted in effect by the plates 22 and 23 on the one hand and the conductive strips 25, the insulation 26 acting as the dielectric. To prevent such loss the modified construction shown in Fig. 5 may be employed.

In this construction the plate electrodes are in the form of metallized areas 34 carried on the inner surfaces of rigid sheets of insulation 35 between the peripheries of which are clamped the conductive strips 25 and diaphragm 21, which components may be as already described with reference to Fig. 3. Components 34 and 35 are perforated, as depicted at 36, for emission of sound. The metallized areas 34 stop short of the diaphragm periphery so that no portions of the plate electrodes constituted by these areas are in register with the conductive strips 25. There is accordingly less capacitive loss in areas not usefully contributing to sound output.

The distance 37 between the periphery of each metallized area 34 and the inner periphery of the strip 25 on the same side of the diaphragm should be great enough to prevent an ionizing discharge but short enough for a fringing field to be established to the furthermost limit of the free diaphragm.

In electrostatic loudspeakers where the signal is applied between the fixed plates, conditions of operation are occasionally such that the signal voltages applied are sufficiently high to cause sparking between the fixed plates through the diaphragm. This damages the diaphragm and is acoustically unpleasant. Although it is possible to prevent this by sheathing the fixed plates in insulating material, practical difficulties are experienced in the production of perforated sheathed electrodes in keeping the sheathing continuous.

By the use of a perforated dielectric shield 41 (see Fig. 6) of high permittivity placed between each fixed electrode 42 and the diaphragm 43, the field conditions may be arranged to preserve the field strength in the major portion of the air gap, and therefore not substantially to alter the operating conditions of the loudspeaker. By doing this, however, the distance between the fixed electrodes has been increased and the field strength in the air between the conducting surfaces through the perforations substantially reduced. In order to maintain the polarizing field in the gap, and to prevent the dielectric shield 41 acquiring a charge, the material of the shield should have sufficient conductivity to prevent charges due to ionic conduction from the diaphragm from accumulating on them and should be in electrical contact with the adjacent fixed electrode.

The loudspeaker may be arranged so that the diaphragm forms to a large extent its own insulating support. Such an arrangement is shown in Fig. 7 for a loudspeaker unit of the kind described with reference to Fig. 3.

The diaphragm 21 is clamped between the insulation strips 26 direct. In place of the conductive strips 25 of the Fig. 3 arrangement, polarizing electrodes in the form of conductive strips 44 are adherently in contact with a free part of the diaphragm adjacent to the peripheral part fixed between strips 26. The clearance between strips 44 and 26 may be of the order of one eighth of an inch. The polarizing voltage is applied to strips 44 by insulated connections (not shown) brought through the periphery of the unit at some convenient point.

Strips 44 may be "printed" on the diaphragm or may be in the form of graphite-pencilled tracks. Each should extend, parallel to the adjacent fixed periphery of the diaphragm and displaced inwardly from it by the small distance of the order mentioned, throughout the peripheral region of the diaphragm. It is not essential that there should be two such strips, one one each side of the diaphragm, a single strip on one side only may be sufficient.

To prevent flashover between strips 44 and those portions of plates 22 in register with them, shielding strips 45 of insulation are interposed, being secured to the inner surfaces of the plates.

In this arrangement the strips 26 serve mainly to insulate the plates 22 from one another. The high-voltage insulation between diaphragm and plates is here provided to a large extent by that part of the diaphragm between the conductive strips 44 and the fixed periphery of the diaphragm. A considerable saving of insulating material is thereby effected.

Shields 45 are not required where the loudspeaker is of the type described with reference to Fig. 5, so long as strips 44 are spaced sufficently outwardly from the metallized areas 34 to prevent flashover. Polarizing strips 44 again replace strips 25, the arrangement being as shown in Fig. 8.

The physical properties, such as their flatness and lightness, of electrostatic loudspeaker units in accordance with the invention make them suitable for combination in arrays. Some arrays of such units will now be briefly considered.

Where economy of space is to be considered, the units may be arranged in a zig-zag formation, as shown in Fig. 9. Since a considerable area of each diaphragm is effective in moving the air through the relatively small exit port 51 of each V-shaped cavity, quite a large amplitude of vibration is produced there by quite a small amplitude of vibration of the diaphragm. Because of this it is possible to reduce the spacing between the diaphragm and the plate electrodes and to employ a lower polarizing voltage and signal voltages, facilitating the design of the output transformer. The depth 52 of each V-shaped cavity should not be substantially greater than a quarter of a wavelength of the highest frequency to be radiated.

Where only a small space is available—for instance where the loudspeaker is part of a domestic radio-receiver— the zig-zag formation may be used in the modified form shown in Fig. 10. The plate electrodes 53 are stacked in parallel with each other by two frames 54 of insulating material, the arrangement being such that adjacent plates have opposite edges free. The spacing between electrodes is shown much exaggerated. The diaphragm 55 takes the form of a continuous sheet which interleaves the fixed plates in a zig-zag manner, passing over each of the free edges in turn, each edge being insulated where the diaphragm passes over it. Each plate 53 (except the two outermost plates at the ends of the stack) thus serves as the outer electrode of two adjacent loudspeaker units. The supporting frames 54 are designed to allow the emission of sound waves from between consecutive electrode plates; the latter accordingly need not be perforated. Since each plate (except the two outermost) forms part of two units it is subjected in operation to equal and opposite electrostatic forces and hence need not be of great rigidity; each plate may accordingly be in the form of a sheet of non-conducting material the surfaces of which carry a metallic coating.

In a development of the foregoing arrangement (see Fig. 11) the stack of fixed plates may be self supporting, instead of being supported by frames. Each plate 56 rests on the plate beneath, as depicted in the lower part of the drawing, with a portion of the diaphragm 57 intervening. As with the embodiment of Fig. 10, the diaphragm is again in the form of a single sheet, being separated by insulation 58 where is passes over the edge of a plate; this is clearly depicted in the upper part of the drawing, where two of the plates are shown widely spaced apart to reveal the method of construction. The edge of each plate opposite to that over which the diaphragm passes has several short strips 59 of insulation folded over it at widely spaced intervals to insulate the plate from the diaphragm where is passes over the edges of the plates on each side and to maintain a space between consecutive plates to allow vibration of the diaphragm.

The sound waves issue through the gaps 60 between the spaced strips 59 of insulation. The assembly is retained in position by two vertical U-shaped channels which contain the respective ends of the plates. One of these is shown at 61, the other being omitted for clarity. Connections from alternate plates are made to a lead 62, contained in channel 61, the intervening plates being connected to another lead 63.

If in a large composite loudspeaker the frequency range is divided and applied to separate sections of the whole area, then it is possible to arrange matters so that the depth of a complete folded loudspeaker is no longer limited by the quarter-wavelength restriction previously mentioned. By way of example, a complete loudspeaker can be folded as in Fig. 12, so as to have two side panels 65 and 67 and a rear panel 66. If the two side panels 65 and 67 are arranged to handle low frequencies only, then the dimensions can be arranged so that acoustic resonances which would normally be associated with the cavity depth 68 occur at frequencies above the upper frequency limit of the side panels. Since these side panels are not themselves producing energy at the resonance frequencies concerned and are of low mechanical impedance it follows that they are acoustically transparent and the complete system behaves as if there were no resonant enclosure.

In each of the arrangements of Figs. 9 to 12 the polarizing potential may be applied to the diaphragm in any convenient manner. Where the polarizing electrodes are not carried by a free part of the diaphragm, they should advisably be inserted at each of the points where the diaphragm is supported in order to avoid leakage paths discharging the diaphragm, as in the arrangements of Figs. 3 to 5.

Although in the foregoing descriptions the applications of the invention have been confined to individual units, such applications are by no means so restricted. By way of example, Fig. 13 shows a diametrical section through a circular composite unit, with the thicknesses of the components again exaggerated. The circular diaphragm 71 is rendered conductive over two separate portions, an annular portion 72 lower-frequency reproduction, and concentric with it a circular portion 73 for upper-frequency reproduction; in effect, therefore, two separate diaphragm electrodes 72 and 73 are provided.

The corresponding plate electrodes are similar to the kind already described with reference to Fig. 5. Those associated with diaphragm electrode 72 are in the form of annular metallic films 74 carried on the inner surface of rigid discs 75 of insulation. Annular conductive strips 76 are employed as before to apply the high potential to the periphery of diaphragm 72. Perforations 77 are formed through discs and films for the emission of sound.

The plate electrodes associated with diaphragm 73 are in the form of circular metallic films 78 also carried by discs 75. Annular conductive strips 79 engage the periphery of diaphragm 73. Discs 75 are so moulded that films 78 are located nearer the associated diaphragm 73 than are films 74 to the associated diaphragm 72, since the latter requires a greater amplitude of vibration. These different spacings require the application of different polarizing potentials; no difficulty is experienced in applying these since conductive strips 76 and 79 are electrically independent.

Where the diaphragm electrode is small compared with the wavelength radiated the frequency response may be equalised by mounting the loudspeaker unit 81 (see Fig. 14) as the front closure member of a shallow box 82 the back closure member of which is a stretched membrane 83 of thicker material than the diaphragm electrode of the unit. At the higher frequencies the diaphragm vibrates alone, the backward radiation being cushioned by the air in the box without causing appreciable vibration of the membrane because of the latter's greater mass. At the lower frequencies the diaphragm and the membrane together with the air enclosed between them vibrate as a whole; the mass of the air and the mass of the membrane are thus effectively added to the mass of the diaphragm and so reduce the bass resonance frequency.

A stereophonic two-channel sound system having the novel acoustic properties described in the following paragraph may be attained from an array of spaced units by arranging them for AF energization as the consecutive elements of a delay line, which itself is energized at each end by signals derived from different channels.

By way of example a number of units may be mounted side by side across the wall of a room each unit being coupled to the adjacent unit by a suitable inductor. If a signal is now fed in at one end of this structure, which forms a delay line, there will be a time delay in the electrical signals applied to the loudspeaker surface across the room. It follows that the wavefront of the sound will no longer be parallel with the loudspeaker diaphragm, but will be tilted. A separate signal fed in to the other end of the delay line will produce a wavefront of the same tilt but in the opposite direction. Since the perceived direction of a source of sound is always perpendicular to the wavefront it follows that the observer will perceive two sound sources the aspect angle of which is constant and entirely independent of the listener's position over a large area. Such an arrangement is shown in Fig. 15. The delay line is formed by connecting together in series an appropriate number of inductors 85 to form a series path 86 and interconnceting opposite points on the path by way of the plate electrodes of loudspeaker units 88, which accordingly act as shunt capacitors. The diaphragm electrodes are connected in parallel to one pole of a source 89 of high potential the other pole of which is earthed. Incoming signals are applied by way of transformers 90 to the ends of the line, these signals being derived from appropriately spaced microphones (not shown) at the transmitting station.

The series inductors 85 need not be separate components. The plate electrodes of each unit 88 may themselves be made inductive—for example, by being formed of spiral conductive tracks sprayed on perforated insulating plates, the perforations lying in between the turns of the spiral coil.

A true binaural effect may be achieved, in a loudspeaker of large total area with its units mounted in side-by-side relationship across an auditorium, by scanning the units horizontally, and if necessary vertically, in synchronism with a similar scanning of an array of microphones at the transmitting studio. Scanning may be accomplished electronically or by a simple rotating selector switch.

In such a case there is reproduced in the auditorium a replica of the sound waves passing through a plane in the concert hall.

This feature of an electrostatic loudspeaker of large total area is of importance in cinema applications, especially where the radiating surface forms the screen on which the picture is projected. For this purpose the outside surface of one of the perforated plates of the loudspeaker may be treated with reflecting beads in the manner of a cinema screen, or preferably embossed with a pattern of small lenses calculated to give the correct light distribution.

WHAT WE CLAIM IS:—

1. An electrostatic loudspeaker unit comprising two rigid plate electrodes in close parallel relationship insulated from one another and secured between them a diaphragm electrode of flexible material the electrical resistivity of the surface of which lies within a range of the order of 2×10^9 to 1×10^{12} ohms per unit square, there being provided at least one polarizing electrode in contact with the diaphragm.

2. A loudspeaker unit as claimed in

Claim 1 wherein the diaphragm electrode is of nylon.

3. A loudspeaker unit as claimed in either of the preceding claims wherein portions of the diaphragm electrode are mechanically loaded by being thickened by the same or other material, thereby improving the bass response.

4. A loudspeaker unit as claimed in any of the preceding claims wherein said polarizing electrode is in contact with substantially the whole of the periphery of the diaphragm electrode and is insulated from both the plate electrodes.

5. A loudspeaker unit as claimed in Claim 4 wherein no portions of the plate electrodes are in register with said polarizing electrode, thereby reducing capacitive loss in areas not usefully contributing to sound output.

6. A loudspeaker unit as claimed in any of Claims 1 to 3 wherein said polarizing electrode is adherently in contact with a free part of the diaphragm electrode adjacent to a fixed part thereof, the arrangement being such that the portion of the diaphragm between said parts serves as some at least of the insulation between the polarizing electrode and the plate electrodes.

7. A loudspeaker unit as claimed in Claim 6 where a portion of the inner surface of a said plate electrode is in register with said polarizing electrode, wherein a shield of insulation is interposed between said portion and said polarizing electrode to prevent flashover.

8. A loudspeaker unit as claimed in any of the preceding claims wherein the plate electrodes are perforated for the emission of sound waves.

9. A loudspeaker unit as claimed in Claim 8 wherein there is interposed between the diaphragm electrode and each plate electrode a perforated dielectric shield in electrical contact with the adjacent plate electrode and of sufficient conductivity to conduct to that electrode any charges acquired by the shield due to ionic conduction from the diaphragm.

10. A loudspeaker unit as claimed in any of the preceding claims wherein the unit is mounted as the front closure member of a shallow box the back closure member of which is a stretched membrane of thicker material than the electrode of the unit, whereby lower bass resonance is attained.

11. A loudspeaker stage including at least one electrostatic loudspeaker unit as claimed in any of the preceding claims, driving means for applying an audio-frequency signal to the plate electrodes of the unit, and polarizing means connected to said polarizing electrode, or to each polarizing electrode, as the case may be, for maintaining the diaphragm electrode at a high uniform electrostatic charge with respect to the plate electrodes.

12. An array of electrostatic loudspeaker units each as claimed in any of Claims 1 to 3 wherein the units are stacked with all the plate electrodes parallel and with the diaphragm electrodes in the form of a continuous sheet which interleaves the plate electrodes in a zig-zag manner.

13. An array of electrostatic loudspeaker units as claimed in any of Claims 1 to 9 wherein the units are of rectangular shape and are assembled in a zig-zag formation.

14. A loudspeaker stage including an array of electrostatic loudspeaker units as claimed in either Claim 12 or Claim 13, driving means for applying an audio-frequency signal to each pair of plate electrodes of each unit, and polarizing means for maintaining each diaphragm electrode at a high uniform electrostatic charge with respect to the plate electrodes of the associated unit.

15. An array of electrostatic loudspeaker units each as claimed in any of Claims 1 to 9 wherein each unit is adapted to be energized by an audio-frequency signal within a frequency band individual to that unit.

16. A loudspeaker stage including an array of electrostatic loudspeaker units as claimed in Claim 15, driving means for applying signals in appropriate frequency bands to the respective pairs of plate electrodes of the units, and polarizing means for maintaining each diaphragm electrode at a high electrostatic charge with respect to the plate electrodes of the associated unit.

17. A loudspeaker stage including an array of electrostatic loudspeaker units in side-by-side relationship each unit being as claimed in any of Claims 1 to 9, the units being connected for audio-frequency energization of the respective pairs of plate electrodes as consecutive shunt elements of a delay line, means for energizing said delay line at each end by audio-frequency signals derived from different channels, whereby a binaural effect is attained, and polarizing means for maintaining each diaphragm electrode at a high electrostatic charge with respect to the plate electrodes of the associated unit.

18. A loudspeaker stage including an array of electrostatic loudspeaker units each unit being as claimed in any of Claims 1 to 10, the units being folded so as to present two side panels and one rear panel, driving means for applying to each pair of plate electrodes of the units audio-frequency signals in only a lower-frequency band, further driving means for applying to the plate electrodes of only the rear panel audio-frequency signals in only a higher-frequency band, and polarizing means for maintaining

each diaphragm electrode at a high electrostatic charge with respect to the plate electrodes of the associated unit, whereby the side panels are acoustically transparent and the loudspeaker behaves as if there were no resonant enclosure.

19. A loudspeaker unit, stage, or array substantially as hereinbefore described with reference to the accompanying drawings.

M. E. SIONS,
Agent for the Applicants.

PROVISIONAL SPECIFICATION.

Improvements relating to Electrostatic Loudspeakers.

We, FERRANTI LIMITED, a Company registered under the laws of Great Britain, of Hollinwood, in the County of Lancaster, and PETER JAMES WALKER, a British Subject, c/o The Acoustical Manufacturing Co. Ltd., Huntingdon, County of Huntingdon, do hereby declare this invention to be described in the following statement:—

This invention relates to electrostatic loudspeakers, by which term is meant a loudspeaker which depends for its action on the force of electrostatic attraction between a movable or flexible diaphragm electrode and a rigid plate electrode secured closely parallel to it.

To reduce non-linear distortion it is usual to locate the diaphragm between two such fixed plate electrodes, one at least of which may be perforated or may be of lattice construction to allow motion of air through it.

To increase the sensitivity and avoid a frequency-doubling effect caused by attraction taking place on both halves of the signal waveform it is also usual to apply a steady polarizing voltage so as to maintain a constant difference of potential between the diaphragm on the one hand and each of the two fixed plates, the plate potentials with respect to the diaphragm being of opposite sign.

The polarizing and audio-frequency signal voltages may be applied in either of two ways:—

(1) the positive terminal of the polarizing source is connected to one fixed plate and the negative terminal to the other fixed plate, the signal voltage being applied between the diaphragm and the point of mid potential of the polarizing source; or

(2) the signal voltage is applied by way of a transformer to the fixed plates and the polarizing voltage is applied between the diaphragm and a centre tap on the transformer secondary.

For good sensitivity the polarizing voltage should be high, and difficulty has been experienced with known arrangements of the above-described kinds through the tendency of a spark discharge to occur between the diaphragm and the plates.

With arrangement (2), the damaging effect of such a discharge may be reduced by inserting a resistance of high value in the connection between the polarizing source and the diaphragm; this resistance has the effect of preventing the full polarizing voltage from being applied continuously once a spark current develops but does not prevent a spark from occurring. With loudspeakers of all but the smallest size, however, this arrangement is not satisfactory because the capacitive charge stored in the loudspeaker is considerable and sufficient in itself to cause damage if a spark should occur.

With arrangement (1), the insertion in the connection to the diaphragm of a resistance large enough to prevent sparking is not practicable because this connection now carries the signal currents and the presence of such a resistance would increase the time-constant of the circuit too much.

An object of the present invention is to provide an improved electrostatic loudspeaker.

A further object of the invention is to provide an electrostatic loudspeaker which allows the use of a high polarizing voltage without the disadvantage above referred to.

In accordance with the present invention an electrostatic loudspeaker includes one or more loudspeaker units each of which comprises two rigid outer plate electrodes having between them a diaphragm electrode of flexible material the electrical resistance of which material is high enough to allow the unit to be polarized by a high direct voltage substantially without sparking between said electrodes when in operation, the unit being adapted to be energized by audio frequency voltages applied to the said outer electrodes only.

Where the loudspeaker has a plurality of said units, said electrodes may be of rectangular shape and the units may be assembled in a zig-zag formation, the said outer electrodes having apertures for the emission of sound waves; alternatively, said units may be stacked with all the said outer electrodes in parallel with one another and the diaphragms form a continuous sheet which interleaves said outer electrodes in a zig-zag manner, the said outer electrodes being spaced apart to allow vibration of the diaphragms and emission of sound waves.

The frequency response of each or any of said units may be substantially equalized by energizing the unit by two transformers one of which has a good response at low frequencies only the other a less but steady response at higher frequencies; or by thickening parts of the diaphragm thereof or by loading said parts with portions of other material; or by mounting the unit as the front closure member of a shallow box the back closure member of which is constituted by a stretched membrane of thicker material than the diaphragm of the unit.

Means may be provided for deriving from the variations of the interelectrode capacitances of a unit during the vibration of the diaphragm thereof a feedback voltage whereby improved linearity of amplitude response is attained.

Said units may be connected for energization by the audio-frequency signals as the consecutive elements of a delay line; in which case the delay line may be fed at a plurality of points by signals derived from a plurality of channels, whereby a binaural effect is attained.

Where the resistivity of the air gap between said electrodes varies with humidity, the resistivity of the diaphragm may be arranged to be such as to vary correspondingly with humidity, whereby the ratio of the resistances of the air gap and diaphragm is maintained constant.

In carrying out the invention in accordance with one form by way of example, an electrostatic loudspeaker includes a number of loudspeaker units each of which comprises a flexible diaphragm of resistive sheet material sandwiched between two closely-parallel metallic plate electrodes of rectangular shape and roughly 5″×25″ size. The plates are thick enough to be rigid and both of them are perforated to provide apertures for the emission of sound waves and prevent "cushioning" of the vibration. The diaphragm is secured in tension by being clamped near its edges between the plates, strips of polythene or other convenient insulating material being interposed between the clamped portions of the diaphragm and the plates to ensure that the diaphragm is insulated from the plates. The spacing between the diaphragm and the plates is sufficient to allow free vibration of the diaphragm at the maximum amplitude required. Suitable terminals are provided in electrical connection with each plate and the diaphragm. The units may be assembled side by side with the outer surfaces of the perforated plates coplanar. Other possible assemblies will be discussed later.

In operation, the two plate terminals of each unit are connected respectively to the ends of the secondary winding of a signal output transformer common to all the units and energized by the final stage of signal amplification. Each unit is polarized by connecting a source of high tension of about 1kV between the diaphragm and a centre tap on the transformer secondary; as a safety precaution the perforated plate, being the more accessible of the two plates, is connected to earth.

The loudspeaker above described is found to give good results, the resistance of the diaphragm being high enough to prevent sparking in normal operation; if a spark should occur in some small area of the diaphragm, the discharge current flowing in the areas adjacent to the discharging area causes the potential of the latter area to be reduced below the value required to maintain the discharge. Only a very small charge is dissipitated before the voltage becomes thus reduced and the spark is accordingly rendered harmless. It will be noticed that the energizing system is that of arrangement (2), previously mentioned, that is, the AF currents which energize each unit flow only in the outer electrodes; a diaphragm resistance that is high enough to prevent sparking is too high for the diaphragm to take the AF currents—in accordance with arrangement (1)—without considerable attenuation and distortion.

Some arrangements of the loudspeaker units will now be briefly referred to.

Where economy of space is to be considered, the units may be arranged in a zigzag formation. Since a considerable area of each diaphragm is effective in moving the air through the relatively small exit port of each V-shaped cavity, quite a large ampli tude of vibration is produced there by quite a small amplitude of vibration of the diaphragm. Because of this it is possible to reduce the spacing between the diaphragm and the fixed plates and to employ a lower polarizing voltage. The depth of each V-shaped cavity should not be substantially greater than a quarter of a wavelength of the highest frequency to be radiated.

Where only a small space is available—for instance where the loudspeaker is part of a domestic radio receiver—the zig-zag formation may again be used. The fixed plates or outer electrodes are stacked in parallel with each other by two frames of insulating material, the arrangement being such that adjacent plates have opposite edges free. The diaphragm takes the form of a continuous sheet which interleaves the fixed plates in a zig-zag manner, passing over each of the free edges in turn, each edge being insulated where the diaphragm passes over it. Each fixed plate (except the two outermost plates at the ends of the stack) thus serves as the outer electrode of two adjacent loudspeaker units. The supporting frames are designed to allow the emission of sound waves from between consecutive fixed plates; the latter are accordingly not perforated. Since each plate (except the two outermost) forms part of two units it is subjected in operation to equal and opposite electrostatic forces and hence need not be of great rigidity; tach plate may according be in the form of a sheet of non-conducting material the surfaces of which carry a metallic coating.

In a development of the foregoing arrangement the stack of fixed plates may be self supporting, instead of being supported by frames. Each plate rests on the plate beneath, with a portion of the diaphragm intervening. The edge of each plate opposite to that over which the diaphragm is folded has several short strips of insulation folded over it at widely spaced intervals to insulate the plate from the diaphragm where it passes over the edges of the plates on each side and to maintain a space between consecutive plates to allow vibration of the diaphragm. The sound waves issue through the gaps between the spaced strips of insulation. The assembly is retained in position by two vertical U-shaped channels which contain the respective ends of the plates.

As with other loudspeakers, radiation from the back surface of the diaphragm must be prevented from reaching the listener. As the acoustic behaviour of an electrostatic loudspeaker of large total area is different from that of a conventional moving-coil loudspeaker, different methods of suppressing the back radiation are required. The assembly of units may for example be mounted in side-by-side relationship across a whole or part of a room. Or the units may be arranged in a corner of a room so that the front surfaces of the electrode combine to form a quadrant of the curved surface of a vertical cylinder the axis of which coincides with the vertical line of the corner and the height of which is comparable with the height of the room. Or the front surfaces may be combined to form a concave surface to focus the sound energy at a selected point; with this arrangement there is a distinct focussing of the higher frequencies, which appear to originate from the axis of the cylinder. Speech, in particular, because of the absence of very low frequencies, appears to emanate from the restricted area of the focus and therefore sounds more natural than if it were radiated diffusely.

The electrical characteristics of the electrostatic loudspeaker facilitate the electrical equalization of the frequency response. For example, when the back radiation is enclosed, the electrical impedance of an electrostatic loudspeaker rises at low frequencies. To take advantage of this characteristic the loudspeaker is fed by two transformers. One of these has a low primary inductance and a low turns ratio so that its response is approximately proportional to frequencies up to, say, 200 c/s and thereafter maintains a value (determined by the turns ratio) which is approximately constant with frequency. The other transformer has a large primary inductance with a large turns ratio and is shunted by a condenser so as to resonate at a frequency of, say, 20 c/s. The combined output voltage therefore rises sharply with frequency to 20 c/s and thereafter falls to the steady value determined by the low ratio transformer. The higher voltage thus available at low frequencies compensates for the low frequency attenuation caused by the enclosure and as a result the power output is substantially constant with frequency.

Where the diaphragm area is small compared with the wavelength radiated, the frequency response may also be equalized by thickening parts of the diaphragm or loading them with button-shaped portions of other material. At the higher frequencies these loaded parts remain relatively stationary and vibrational displacement occurs mainly in the intermediate areas of low mass, from which areas effective treble radiation takes place. At the lower frequncies the diaphragm vibrates as a whole, thereby providing effective bass radiation.

In a further arrangement for this purpose a loudspeaker unit, as first described above, may be made to form the front closure member of a shallow box the back closure member of which is a stretched membrane of thicker material than the diaphragm. At the higher frequencies the diaphragm vibrates alone, the backward radiation being cushioned by the air in the box without causing appreciable vibration of the membrane owing to the latter's greater thickness. At the lower frequencies both the diaphragm and the membrane and the air enclosed between them vibrate as a whole; the mass of the air and the mass of the membrane are thus effectively added to the mass of the diaphragm and so produce more effective bass radiation.

In each of the embodiments so far described, improved linearity of amplitude response may be achieved by the use of feedback derived from the variation in interelectrode capacitance caused by the vibration of the diaphragm. A circuit for doing this will now be described.

Each loudspeaker unit may be considered as two variable condensers in series, having the diaphragm as a common electrode. The common point of these two condensers (the diaphragm) is connected by way of the polarizing source to the centre tap of the transformer secondary, as already described. The two condensers can therefore be further considered as the two adjacent arms of a bridge network, the other adjacent arms of which are the two halves of the secondary winding. In the present arrangement an impedance, which may be in the form of a tuned circuit, is connected in series between the diaphragm and the polarizing source, a radio-frequency voltage is applied across the other diagonal of the bridge—i.e., across the fixed plates of the loudspeaker unit—, and the out-of-balance voltage thereby set up across the impedance is rectified and applied as the feedback to the audio amplifier. Where the impedance of the two halves of the secondary winding is not predictable these two arms of the bridge may be constituted by two condensers, connected respectively across the windings to by-pass them at radio frequencies. To isolate the windings from the RF currents a rejector circuit is connected between each end of the secondary and the corresponding condenser.

If the balance point of the bridge is reached when the diaphragm is central, the amplitude of the out-of-balance signal represents only the extent of the displacement of the diaphragm, and the direction of the displacement is represented by the phase of the RF current. The rectifier, therefor, must be some special form of phase sensitive rectifier. Alternatively, the capacitance of one of the additional condensers may be increased so that a balance is reached when the diaphragm is at its maximum displacement. The feedback voltage is then represented by the variation of the out-of-balance RF about some mean value. In this case only a simple rectifier circuit is required.

Where the circuit is arranged to be balanced when the diaphragm is central, an RF voltage of constant amplitude may be added to the out-of-balance voltage before rectification.

Where difficulty is experienced in maintaining signal voltages across the units of a loudspeaker and in matching them to the output stage of the audio amplifier, the units may be connected in series with inductors for AF energization as the consecutive elements of a delay line designed to have a cut-off frequency in the ultrasonic frequency range so that its transmission characteristics are sensibly constant with frequency over the audio range. The line may be terminated in its characteristic impedance and as many loudspeaker units as are required may be added without altering the impedance presented to the amplifier output circuit.

Alternatively, the line may be left unterminated so that at least a portion of the energy reflected from the open end is radiated from the units in its second passage along the line. Greater efficiency is thus possible.

Because of the delay associated with each unit, an electrostatic loudspeaker comprising many units exhibits a reverberation effect. This apparent reverberation is increased by the use of an unterminated line and this is considered a desirable feature since it lends an illusion of distance and spaciousness not normally associated with listening in small rooms.

The delay line is a lossy one, for some energy is radiated acoustically by each unit and the voltage available at successive units will diminish. To distribute the power loss equally among the units the impedance of the line may be made to rise towards the end by suitable adjustment of the value of the series inductors and/or the capacitance as represented by the area of the units, or by use of transformer couplings.

The series inductors need not be separate components. The fixed plates of each unit may themselves be made inductive, for example by being formed of spiral conductive tracks sprayed on perforated insulating plates, the perforations lying in between the turns of the spiral coil.

The power loss may also be distributed by so adjusting the series inductors and/or the capacitance of the units as to achieve a progressively lower frequency cut-off along the line. The bass response is thus approximately uniform along the line whereas the treble response falls off after the first few units. Such an arrangement compensates for the relatively low bass response of electrostatic loudspeakers.

As was stated above, the connection of several loudspeaker units as an unterminated delay line has the effect of increasing the reverberation time. In a two-channel system of sound reproduction the two outputs may be applied to opposite ends of the delay line. Two sources of sound are thus produced from the diaphragm of each unit. In general, because of the "tilt" introduced at each unit and the consequent tilting of the radiating acoustic wavefronts in opposite senses, the two sources will appear to be separate. This arrangement has the advantage over arrangements employing two separate loudspeakers in that each signal uses the whole of the radiating surface, thereby producing greater response.

The delay line may be fed by two channels in other ways, for example one input at the centre of the line and the other input, by way of an adjustable amplifier, to one or both ends, to give the effect of a source near to the listener and a second source more distant. The illusion of nearness is conveyed partly by suitably adjusting the volume in the latter channel and partly by the short reverberation time associated with the centre-fed signal. If the relative volumes are determined by the distribution of the microphones at the transmitting station, an approximation to a binaural effect may be achieved.

Since the main cause of binaural effects in a concert hall is perception of reverberant sounds, such effects may be achieved realistically in the electrostatic speaker from a three-channel system by feeding the output representing the direct sound into the centre of the delay line and the other two outputs representing the reverberant sounds into opposite ends of the line, thereby producing three apparent sources—one of direct sound and the others of reverberant sound.

A true binaural effect may be achieved, in a loudspeaker of large total area with its units mounted in side-by-side relationship across an auditorium, by scanning the units horizontally, and if necessary vertically, in synchronism with a similar scanning of an array of microphones at the transmitting studio. Scanning may be accomplished electronically or by a simple rotating selector switch.

If a multi-channel system is permissible, one channel being allocated to each microphone and corresponding loudspeaker unit or group of units, then no scanning arrangements are necessary, provided the microphones are sufficiently directive.

In each case there is reproduced in the auditorium a replica of the sound waves passing through a plane in the concert hall.

This feature of an electrostatic loudspeaker of large total area is of importance in cinema applications, especially where the radiating surface forms the screen on which the picture is projected. For this purpose the outside surface of one of the perforated plates of the loudspeaker may be treated with reflecting beads in the manner of a cinema screen, or preferably embossed with a pattern of small lenses calculated to give the correct light distribution.

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Agent for the Applicants.

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FIG. 1.

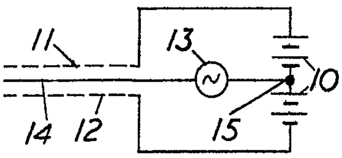


FIG. 2.

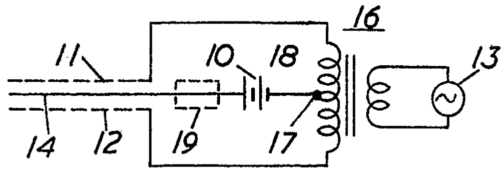
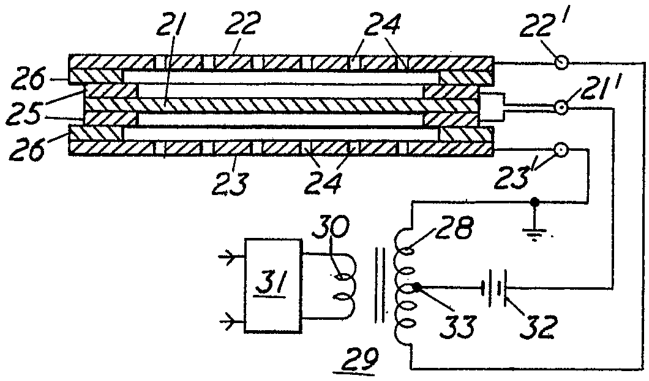


FIG. 3.



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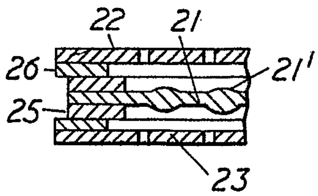
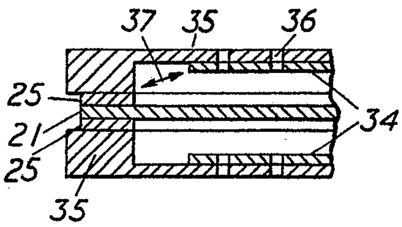


FIG. 5.



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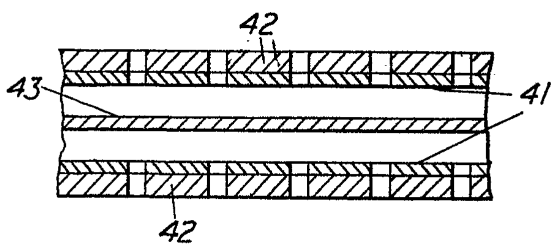

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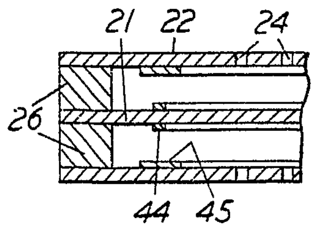

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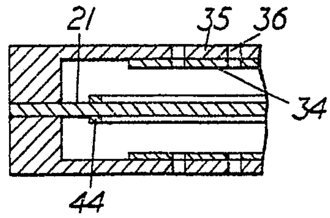
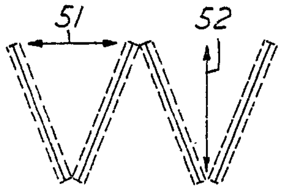
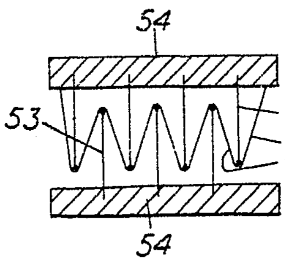


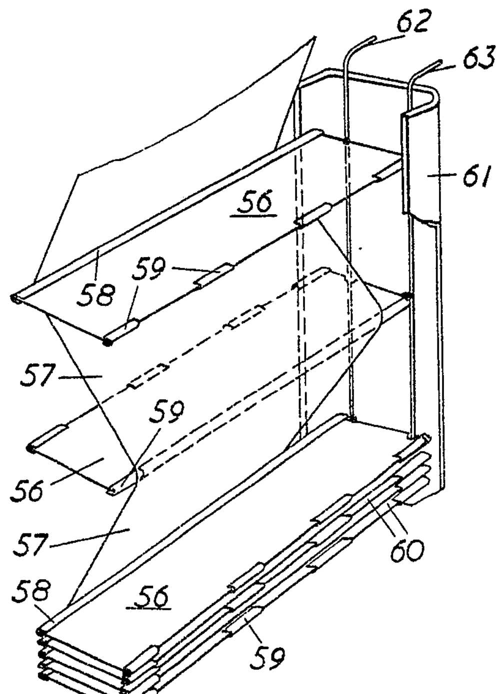
F/G.9.



F/G.10.



F/G.11.



815,978 COMPLETE SPECIFICATION
3 SHEETS
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SHEETS 2 & 3

FIG. 12.

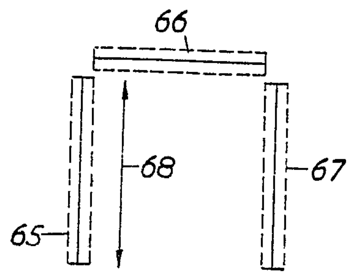
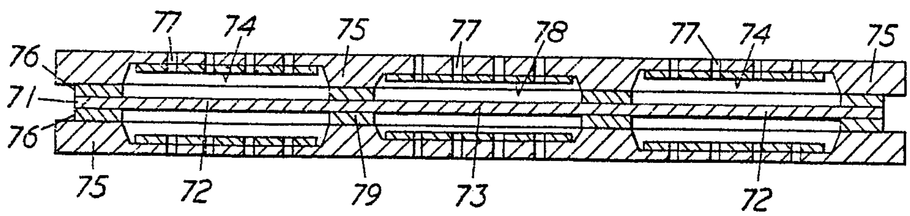


FIG. 13.



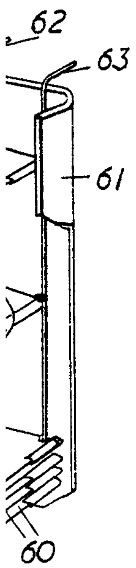


FIG. 14.

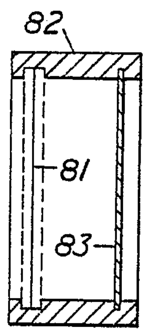
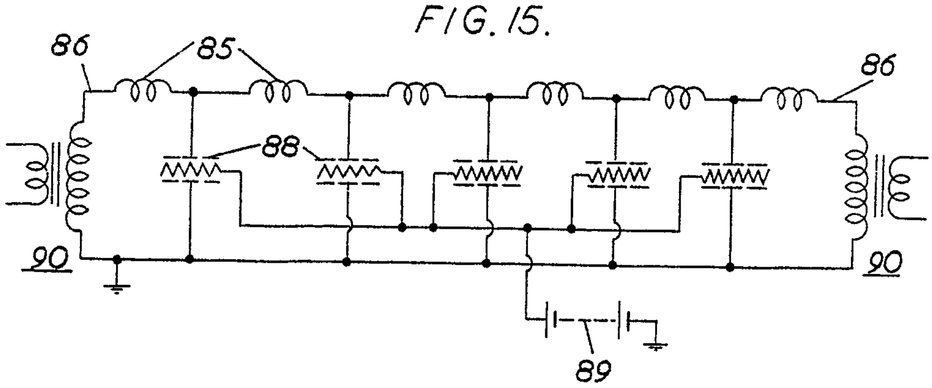


FIG. 15.



815,978 COMPLETE SPECIFICATION
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SHEETS 2 & 3

FIG. 7.

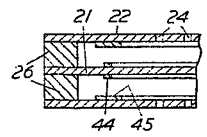

FIG. 8.

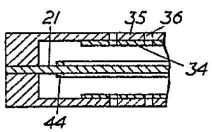

FIG. 9.

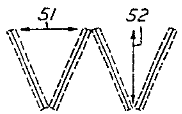

FIG. 10.

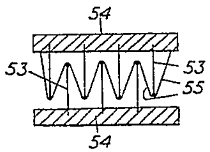

FIG. 11.

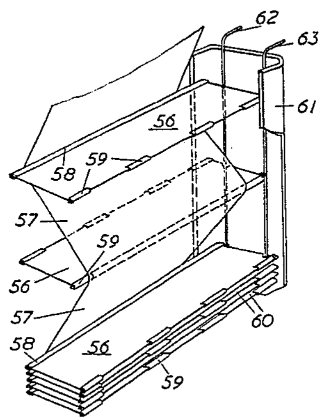

FIG. 12.

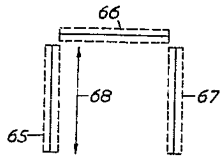

FIG. 13.

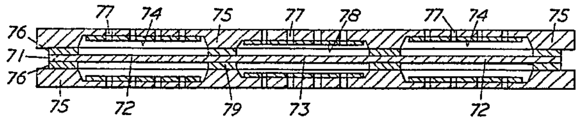

FIG. 14.

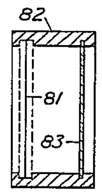

FIG. 15.