By P. J. WALKER

Wide Range Electrostatic Loudspeakers

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Wide Range Electrostatic

1.—*Principles of Design for Operation at Low as well as High Frequencies*

A closer examination of underlying principles leads to the conclusion that the electrostatic loudspeaker may well supersede the moving coil for high-quality sound reproduction. Designs recently developed have proved to be capable of reproducing the full audio-frequency range, with harmonic distortions no higher than those of the associated amplifier.

EVERY loudspeaker designer must, at some time or other, have looked longingly at the electrostatic principal of drive as a solution to his problems of improving quality of reproduction. The movement of a diaphragm driven all over its surface is entirely predictable. The diaphragm can be as light as required. The impedances influencing performance can be predominantly acoustic and—since there are no shape restrictions—entirely under the control of the designer.

What has held it back? First, the fact that *in its generally known form* it is intrinsically non-linear and even in a push-pull construction linearity can only be approached for small amplitudes. Secondly, in order to obtain adequate sensitivity the available gap is small; the diaphragm movement limited and largely stiffness controlled, both factors restricting its use to high frequencies. Thirdly, that being essentially a capacitive electrical load, it is difficult to match to an amplifier.

The first of these objections, that of non-linearity, can be removed completely by an expedient which is spectacular in its effectiveness and simplicity. The second and third difficulties will resolve themselves, as we shall see later, when the designer makes his choice of the interdependent mechanical, acoustical and electrical variables.

Fig. 1 (a) shows diagrammatically the connection of a conventional electrostatic loudspeaker in which the polarizing voltage is applied to the centre diaphragm and the signal in push-pull to the outer perforated fixed plates. Under conditions of no signal, Fig. 1 (b), and assuming the diaphragm to be central, there will be equal and opposite attractive forces on the diaphragm. If one fixed plate is now made positive and the other negative so that the diaphragm will be deflected to the right, the effective capacitance will increase, and to satisfy the relationship $Q=CE$ the charge Q will also increase and will be supplied by a current i during the movement. The force acting on the diaphragm per unit area will, however, be proportional to

$$\left(\frac{E+e/2}{d_2}\right)^2 - \left(\frac{E-e/2}{d_1}\right)^2.$$

The relationship will be non-linear. Note that the charge Q, although varying, does not enter directly into the relation.

Suppose that after having charged the diaphragm electrode the source of polarizing potential is disconnected (Fig. 1(d)). The diaphragm now carries a constant charge Q which experiences a force proporional to the product of the field intensity and the charge. This force will be independent of the position of the diaphragm between the plates since both Q and the distance between plates are constants; the only variable is the applied voltage e. Note that the difference between d_1 and d_2, although varying, does not enter into the relation.

The above is perhaps an over-simplification, but it shows that distortion is not necessarily inherent in the electrostatic principle.

The "constant Q" method of operation has another very important advantage in that it reduces the risk of collapse, which occurs at large amplitudes with the conventional method of connection, when the negative stiffness resulting from electrical attraction exceeds the positive mechanical stiffness of the diaphragm. As the diaphragm approaches one of the fixed plates the capacitance is increased, but as the charge Q has been assumed constant, E must fall since $E=Q/C$.

Professor F. V. Hunt of Harvard University has shown† that the criterion for dynamic stability under large excursions is that the time constant R_0C_0 of the charging circuit (Fig. 1(e)) should be large compared with 1/2f, the half-period of the applied frequency. This also supplies the condition for low distortion and Professor Hunt gives the results of measurements (Fig. 6.14, p. 212, *loc. cit.*) showing the dependence of second harmonic distortion on both the degree of unbalance due to displacement of the central electrode (in terms of $\Delta C/C$) and of the ratio of time constant to half period $2fR_0C_0$. Even when this latter parameter was reduced to unity, and the diaphragm displaced by a distance equivalent to a capacity unbalance of 25 per cent, the second harmonic did not exceed 0.5 per cent, when driven at 150 c/s by 780 V r.m.s. (plate-to-plate) with a polarizing voltage of 500. Third and higher harmonics were always less than the second.

So much for the driving mechanism; it now remains to see how it fares when coupled to the air and to an amplifier.

It will help in understanding the broad principles involved if we start by considering a loudspeaker whose diaphragm is large compared with the longest wavelength of sound to be reproduced. Under these conditions the mass reactance of the air load on both sides of the diaphragm can be neglected and the impedance per unit area $2\rho c$ offered to the motion of the diaphragm is predominantly resistive ($\rho c=42$ mechanical ohms per cm^2). With constant voltage driving the diaphragm the force will be proportional to the applied signal voltage and independent of frequency. If the load is resistive the velocity, and also the acoustic power output, will be independent of frequency.

At very high frequencies the mass reactance of the diaphragm can exceed the radiation resistance and will cause a falling off in velocity when the force remains constant; the acoustic output will then decline by

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* Acoustical Manufacturing Co., Ltd.

† "Electroacoustics" by F. V. Hunt, chapter 6. Published by John Wiley & Sons (Chapman & Hall).

Loudspeakers

with Negligible Distortion

6 db/octave, but, with suitable choice of diaphragm material, not until a frequency of 20 to 25 kc/s is reached. (How different from the average moving coil in which the cut-off starts at about 1,000 c/s and must be sustained by focusing of high frequencies along the axis or by juggling with cone "break-up.")

Similarly at low frequencies a 6 db/octave falling off with reducing frequency will result when the reactance due to the stiffness (reciprocal of compliance) of the diaphragm exceeds the resistance air load. This state of affairs is shown graphically in Fig. 2. Unfortunately, it is not so easy to put the frequency at which the stiffness begins to exercise control outside the audible range. The choice of stiffness will be dictated by the necessity of constraining the diaphragm against the forces associated with the polarizing voltage. Under "static" conditions ($2fR_0C_0$ less than unity) these forces can increase as the diaphragm approaches the fixed plates and must be limited by a suitable choice of stiffness, polarizing voltage and plate spacing. The plate spacing also determines the electrical capacitance of the loudspeaker, and the impedance offered to the amplifier at the frequency chosen for "matching."

Thus the bandwidth available for constant output, under the acoustic conditions postulated, is limited at low frequencies by the diaphragm stiffness required for stability and at high frequencies by the conditions of matching to the amplifier. (The inertia cut-off will always be well above the matching frequency and can be ignored.)

The true efficiency of an electrostatic loudspeaker is very high indeed, but it is difficult to realize because of the large wattless current which has to be provided due to the electrical capacity of the loudspeaker unit. Thus it is necessary to waste watts in the amplifier or in resistances associated with crossover networks of which the loudspeaker may be part. For purposes of simplification, therefore, it is convenient to use the term "apparent efficiency" the meaning of which is the ratio of the acoustic power output of the loudspeaker to the amplifier volt-ampere output necessary to provide the required voltage across the loudspeaker capacity.

The way in which the designer can trade bandwidth for "apparent efficiency" is illustrated by Figs. 3 and 4. In both cases we assume the maximum output will be available at the high-frequency matching limit, and that constant voltage will be available at this and lower frequencies.

In Fig. 3 let curve (a) represent the response with a given electrode spacing $D=1$. If we double the spacing the diaphragm stiffness required for stability

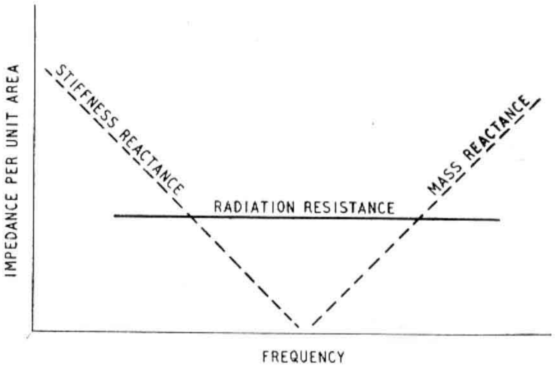


Fig. 2. Variation of acoustical and mechanical impedances with frequency in a diaphragm which is large compared with wavelength.

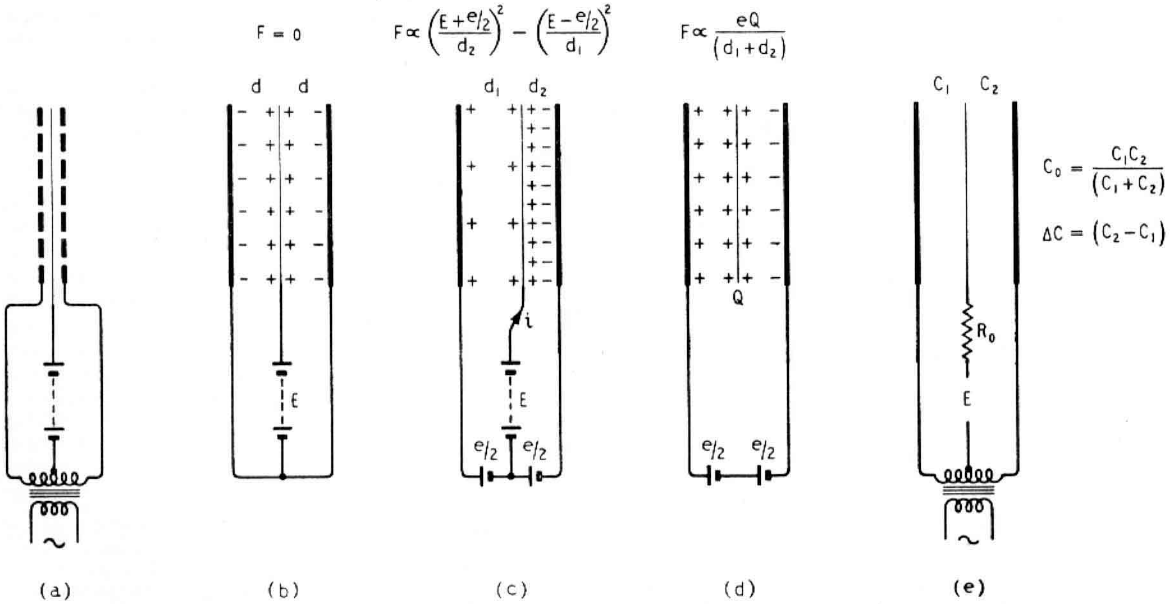
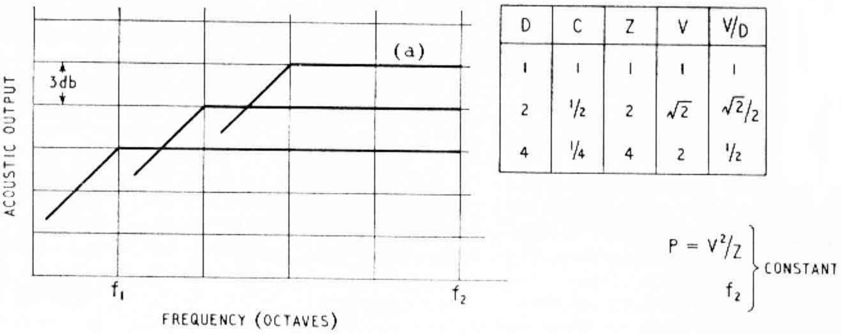
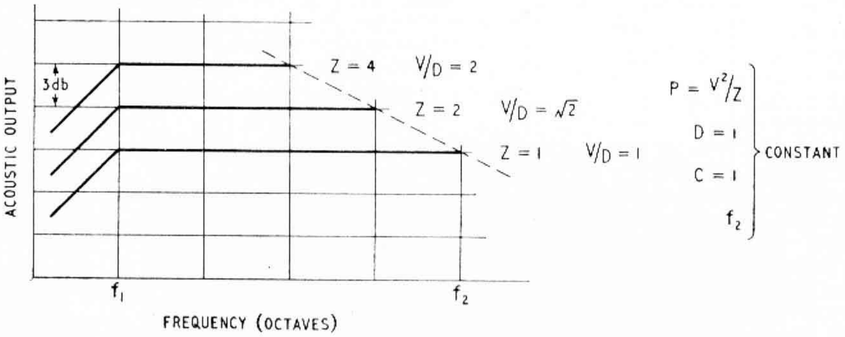


Fig. 1. Essential differences in the operation of electrostatic loudspeakers with "constant voltage" and "constant charge" on the centre diaphragm.

Right: Fig. 3. Low-frequency response can be extended, at the expense of "apparent efficiency," by increasing the plate spacing and re-matching to the amplifier at f_2, the upper frequency limit.



D	C	Z	V	V/D
1	1	1	1	1
2	$1/2$	2	$\sqrt{2}$	$\sqrt{2}/2$
4	$1/4$	4	2	$1/2$



Left: Fig. 4. Alternatively, with constant spacing and a fixed low-frequency limit the high-frequency response can be extended, again at the expense of "apparent efficiency," by varying the frequency f_2 at which the capacitive impedance is matched to the amplifier.

can be halved and the low-frequency cut-off goes down an octave. At D=2 the capacitance is halved and the impedance doubled, but because the power is limited the volts rise by only $\sqrt{2}$ when the amplifier is re-matched. Thus the field strength V/D available to drive the diaphragm is reduced to $\sqrt{2}/2$ and the response falls by 3 db. We have thus gained an octave for a drop of 3 db in output, and, of course, the necessity of finding twice the polarizing voltage.

We can, if required, regain the lost efficiency by re-matching an octave lower at the top end, as shown in Fig. 4. We now keep D (and C) fixed, and with it the low-frequency cut-off. The field strength available for driving the diaphragm will be proportional only to the voltage available from the amplifier. If we re-match an octave lower Z will be doubled and V will increase to $\sqrt{2}$, so there will be a 3-db rise in acoustic power for the loss of an octave at the high-frequency end.

Since very high efficiencies are not a pre-requisite of high-quality reproduction, it is convenient to arrange the apparent efficiency to be similar to the efficiency obtained from present-day commercial moving-coil speakers. Setting the efficiency at this level and applying polarizing voltages permissible in the given air gap, we find that the available bandwidth for level response is about four to five octaves.

Below the low-frequency cut-off we have the stiffness of the diaphragm controlling response, a large proportion of it under conditions where the "apparent efficiency" is high and wasted. (At low frequencies the impedance is high, and less power is required to maintain constant voltage.) Thus, by a progressive change of "matching" in this area, one can compensate to extend the level response below the mechanical cut-off. The effect of this mechanical stiffness is best considered when we deal with possible forms of loading, since it can be lumped in with the acoustical circuit loading the loudspeaker.

A high polarizing voltage is desirable in order to place a high value of charge Q on the diaphragm. Each small unit area of the diaphragm can be fed with a high voltage at very high impedance, thus charging up that part of the diaphragm in relation to the fixed plates. In this arrangement of the loudspeaker, where the signal is applied to the fixed plates only, there are no signal currents due to the wanted signal in the diaphragm itself, so that this arrangement of high-impedance charging of each unit area of the diaphragm is permissible, and is essential for linearity in any practical construction. Any tendency for the air to conduct between the diaphragm and the fixed plate at any point in the loudspeaker merely causes a slight drop in the voltage at that area on the diaphragm, so that in this way high voltages can be applied without any danger of sparking.

Since the charge on the diaphragm is unvarying, it follows that the force on the diaphragm is completely independent of the position of the diaphragm in the space between these electrodes and the system in linear. With this arrangement, then, it is no longer

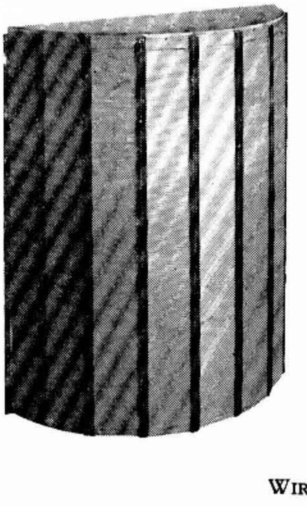


Fig. 5. High-frequency unit with dimensions large compared with wavelength designed to cover frequencies from 1,000 c/s to the upper limit of audibility.

necessary to restrict the allowable motion of the diaphragm to a small percentage of the available gap. Again, there is no restriction to the ratio of signal voltage to polarizing voltage. The only non-linear element entering the system at all is that due to the compliance of the diaphragm, and since in most designs this is not a controlling factor in the motion of the diaphragm its importance is small. There is no difficulty in producing units on this principle, the distortion content of which is even lower than that of present-day amplifiers, and many times better than a moving-coil loudspeaker of normal efficiency.

We have seen, then, that it is now possible to design loudspeakers on the electrostatic principle for a given bandwidth, over which the forces are acting directly on to the air. We have seen that this bandwidth can be placed anywhere in the audio range and that linearity represents considerable improvement on anything hitherto produced. The design of a loudspeaker unit on such principles is therefore purely one of applying it to its acoustical load to give any required performance.

We have so far assumed the simple case of $2\rho c$ loading on the diaphragm. Ignoring for the moment horn loading, this can only be achieved in practice at high frequencies, or for cases where the diaphragm is very large indeed.

A simple single unit construction for high frequencies is shown in Fig. 5. This loudspeaker covers the range from 1,000 c/s to the upper limits of audibility. Such a unit could, of course, be used with conventional moving-coil speakers for low frequencies, but the assumption that moving-coil units operate like distortion-less pistons at low frequencies is very far from the truth. It is obviously desirable to introduce the benefits of the electrostatic principle throughout the whole frequency range.

By way of showing what can be done, Fig. 6 shows a more complex design of electrostatic loudspeaker which, when properly loaded, covers the whole frequency range from 40 c/s up to the limits of audibility. In a future article it is proposed to discuss the operation of such loudspeakers, i.e., when size is no longer large compared to wavelength, and to show the basis of design approach for the whole frequency range.

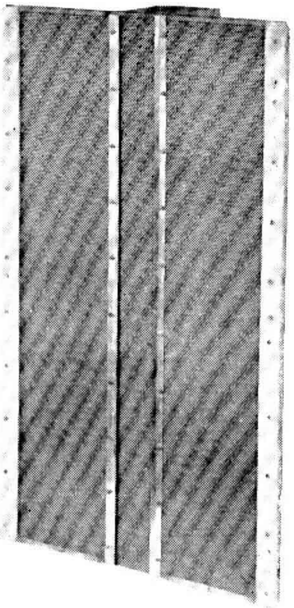


Fig. 6. Unit of more complex design which, with proper acoustic loading, covers the range from 40 c/s to the upper limit of audibility. Measurements on this and the unit of Fig. 5 indicate total harmonic distortions of less than 1 per cent.

Distortion measurements on these units gave figures well below 1%. Measurements were made out of doors, and noise, wind, and other restrictions due to imperfect conditions made it difficult to get reliable figures below 1%. Inspection of the residual waveform indicates that the distortion due to the units is considerably lower than this figure.

Similar remarks apply to frequency response, due to the fact that it is virtually impossible to achieve perfect loading conditions. Measurements produce responses which are within 2 db of the predicted curves, but the major part of these small discrepancies may be attributed to the approximations assumed in the structures used for loading.

Since 1953, electrostatic loudspeakers have been the subject of joint development between Ferranti, Ltd., of Edinburgh, and The Acoustical Manufacturing Co., Ltd., of Huntingdon. Some of the techniques involved in the design of these loudspeakers are the subject of joint patent applications by P. J. Walker and D. T. N. Williamson.

2—Problems of Air Loading

Different Requirements of Moving-coil and Electrostatic Drive Units

IN the first part of this article we showed that it was possible to design and construct electrostatic driving units which were capable of applying a force which virtually acted directly on to the air, and we showed that this force was linear. This state of affairs applied over a bandwidth of several octaves for any single unit, depending upon the efficiency required from that unit, and it was further shown that that bandwidth could be placed anywhere in the audio range.

The only mechanical impedance likely to affect performance is the suspension compliance of the diaphragm, necessary to offset the negative compliance due to electrical attraction. We can therefore begin to draw an electrical analogue circuit of the mechanical elements of the loudspeaker as in Fig. 1, showing the force fed in series with a capacitance. In practice the compliance will considerably exceed the electrical negative compliance, so that this capacitance C_d is almost solely due to the diaphragm compliance.

For simplicity we will restrict consideration to units driven from constant-voltage sources, so that no elements need be included to indicate amplifier source impedance.

Since the loudspeaker will be coupled to the air, we can now add the front air load radiation resistance R_f and the front air load mass, M_f and we can include the impedance Z which represents the impedance presented to the back of the diaphragm.

The impedance Z may include dissipative terms in the form of absorption and/or acoustic radiation resistance. With most acoustic devices the analogy elements change with frequency and the problem, as with all loudspeaker design, is to arrange matters so that the power developed in the radiation resistance(s) is independent of frequency.

The electrostatic unit differs from the moving coil n that there is no large mass component (cone and speech coil) which normally appears as a large inductance in series with C_d. The absence of this inductance profoundly alters the requirements for Z, and since Z is the cabinet or back enclosure it is to be expected that the form of cabinet for electrostatic units will follow trends entirely different from those that have been evolved for moving-coil units. A further difference is that the shape of the diaphragm area is more versatile, so that R_f and M_f may be independently varied over reasonable limits.

Due to the absence of large mass we can, if we wish, arrange the constants so that R_f is large compared with the other elements, and therefore becomes the controlling factor for the equivalent current in the circuit, i.e., the velocity of motion of the diaphragm. This means that the impedance looking back into the loudspeaker can be very low. When this is so, any increase in the acoustic resistance on the front of the diaphragm will result in *reduced* power output. If, on the other hand, the impedance of the loudspeaker is made to appear high by arranging that the total impedance is

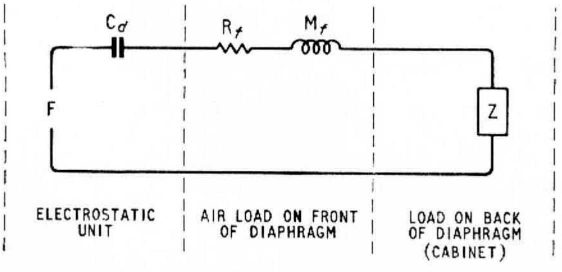


Fig. 1. Elementary equivalent circuit of mechanical and acoustical parameters of an electrostatic loudspeaker.

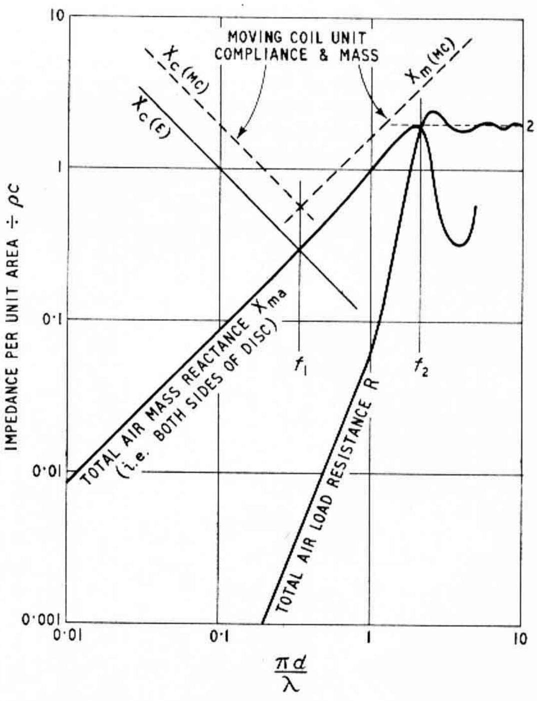


Fig. 2. Mass and radiation resistance loads on circular diaphragm in free air. The normalized frequency scale is in terms of the relationship of diaphragm size to wavelength.

large compared with R_f then an increase in acoustic resistance on the front of the diaphragm will result in *increased* power output. This ability to control the impedance looking back into the diaphragm is a useful feature in designs where R_f is subject to fluctuations due to surroundings, horn reflections, etc., and, in particular, where one loudspeaker unit is influenced by another unit at cross-over frequencies.

In order to show the action of an electrostatic unit which is small compared to the wavelength of the radiated sound it is convenient to commence with a circular shape, because impedance information is readily available for such a shape. Load impedance for other shapes is best obtained by considering the diaphragm as a number of unit areas of equal size and calculating the impedance of each unit area, taking into account the mutual radiation due to the presence of all other unit areas.

Fig. 2 shows the load on a piston operated in an unlimited atmosphere without a baffle. The diaphragm compliance reactance $X_c(E)$ is also drawn. Between f_1 and f_2 the controlling factor is the air mass, and the velocity of motion will vary directly with frequency until resonance between $X_c(E)$ and X_{ma} is approached. R, however, falls rapidly with frequency, and the power output will fall at approximately 6db per octave with declining frequency. (Exactly the same would occur with a moving coil unit, control this time being the mass of cone and speech coil designated $X_m(MC)$. $X_c(MC)$ is the moving-coil suspension compliance.)

Multiple diaphragms without baffles, having the above characteristics, form the basis of design for loudspeakers to provide the directivity of a doublet. Such a system has useful attributes in relation to the listening rooms, a subject to be dealt with in a later article.

Above f_2 the velocity of the moving-coil unit would still be controlled by $X_m(MC)$ (except for cone "break-up") and, since the resistance becomes constant, the response will fall with increasing frequency. In the electrostatic case above f_2 the velocity will be controlled by the air load resistance, and the response will be independent of frequency.

Extending this comparison to units in very large baffles we have the curves of Fig. 3. Here the radiation resistance varies with the square of the frequency below f_2. With a moving coil the response will be level below f_2 and will fall with frequency above f_2. With the electrostatic the response will be level below f_2 and also level above f_2, but there will be a step in response so that the output level above f_2 will be 3db higher than that below f_2.

A simple arithmetical example will make clear the reason for this step. With constant force F applied to the diaphragm, the velocity of movement will be $\dfrac{F}{\sqrt{R^2 + X^2}}$ and the power expended usefully in the radiation resistance will be $P = \left(\dfrac{F}{\sqrt{R^2 + X^2}}\right)^2 \times R$

At f_B in Fig. 3, neglecting Z due to the declining air mass reactance, we have for a constant force $F = 1$, $P = \dfrac{R}{R^2} = \dfrac{2}{4} = \frac{1}{2}$. At f_A, on the other hand, the air mass predominates and, if R can be neglected in calculating the velocity of motion, $P = \dfrac{R}{X^2} = \dfrac{0.01}{(0.2)^2} = \dfrac{0.01}{0.04} = \frac{1}{4}$, or half the power at f_B. A similar relationship will be found for any other pair of values of R and X at points below f_2.

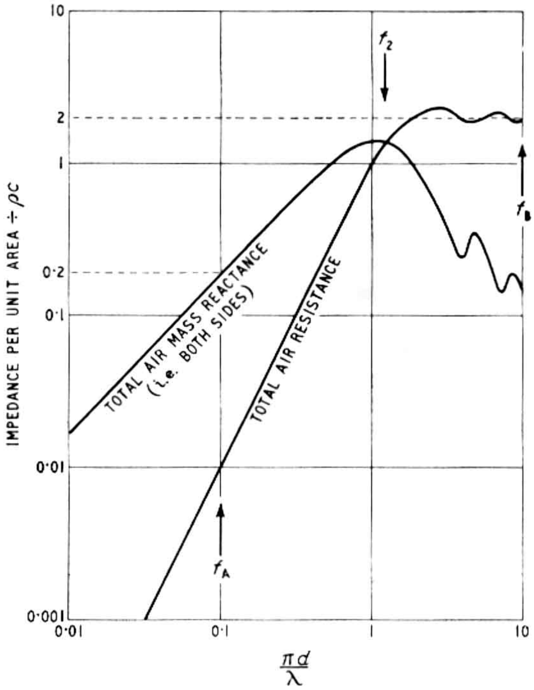


Fig. 3. Mass and radiation resistance curves for a circular diaphragm in a large baffle. The power radiated at any frequency f_A well below f_2 is half that radiated at frequencies f_B well above f_2 (see text).

This change in level can be overcome by deviating from the circular piston shape. For wavelengths large compared to the diaphragm size the resistance per unit area is dependent upon the new area and not upon the shape, whereas the mass is mainly dependent upon the smaller dimension. By elongating the diaphragm shape the output level below f_2 can be made equal to that above f_2.

We have so far been considering a comparatively small diaphragm in a flat baffle, the latter being very much larger than the piston, and the size of the complete system is obviously that of the baffle. The reason that the piston has been kept small is purely for the convenience of the moving-coil unit, because its diaphragm is driven at only one point. In the electrostatic case we no longer have this restriction, and it will always be preferable to increase the size of the piston (without increasing the total size of the complete system). This will usually be necessary because there is a limit to the available amplitude of movement, and thus, for a given power output per unit area, we have a minimum limit to the radiation resistance in order that the diaphragm excursions may be attainable. Increasing the size of the piston for a given power output has the double advantage of reducing power requirements per unit area, and, where the loading is below $2\rho c$, of increasing the radiation resistance per unit area, and therefore reducing the amplitude required to provide that power output. For reasons of efficiency we shall in any case limit the high-frequency response of the unit so that optimum design is obtained by increasing the area of the diaphragm to the point where the piston just begins to become directional at the frequency which we have chosen for cross-over (set by the efficiency laid down in the design requirements).

Continuing the consideration of the air load on diaphragms, reference should be made to horn loading. Here we have large resistive and mass components due to the horn. Fig. 4 shows the load of an idealized horn to which has been added X_m(MC), the cone mass of a typical moving-coil loudspeaker which might be used with such a horn. It will be seen that at low frequencies the cone mass is largely swamped by the horn impedance, so that the design of horns for electrostatic units differs very little from the design for moving-coil units. Although we can now have the advantages of a virtually distortionless driving unit, we are still left with the disadvantages of practical horns, which are present independently of the drive units. Horns are normally used to match the high impedance of moving-coil diaphragms to the low impedance of the air. Since we have no such fundamental mismatch with the electrostatic loudspeaker, and since diaphragm shape and size are not fundamentally restricted, we shall not normally have to resort to the use of horns to the same degree. It should be remembered, however, that any back enclosed volume is a direct function of throat area, so that in some applications it is possible to use space for providing a length of horn in exchange for saving in size of capacitive enclosure. Again, we may wish to restrict the front-wave expansion in order to maintain a reasonable resistance per unit area at low frequencies (utilizing the corner of a room, for example).

One of the most desirable diaphragm shapes for electrostatic designs is that of a strip having a length (together with floor or wall image) large compared to $\lambda/3$ at the lowest frequency of interest, and a width small compared to wavelength at the highest frequency of interest. The strip may be curved along its length if desired, provided the radius of curvature is not less than $\lambda/3$ at the lowest frequency.

To consider the load on such a strip it is convenient to assume the strip as being infinite in length (legitimate provided it is at least $\lambda/3$ in length). With such a diaphragm there will be no expansion of sound in the direction of the length since all pressures along the length of the strip will be equal. Expansion from any given element of the diaphragm takes place in one plane only and will therefore take the form $S = S_0 x$. This is the expansion of a parabolic horn. At low frequencies the front air load resistance is falling directly with frequency (instead of f_2 as with the circular piston shape). The advantages of the strip shape may now be enumerated:—

(a) The air resistance even at low frequencies (since $R \propto f$) is sufficient to develop adequate power with reasonable diaphragm amplitude.
(b) The narrow diaphragm gives good dispersion for several octaves (up to the frequency at which width $\approx\lambda/3$).
(c) The narrow diaphragm enables other units to be placed close to it, thus being less than ¼ wavelength apart at cross-over frequency.
(d) The frequency limitations, amplitude at the low end, and directional problems at the high end, fit in nicely with the 4-5 octave range which we established in Part I of this article for satisfactory efficiency. Thus a strip shape can form one basis of design for our ideal—the perfect loudspeaker.

It will be obvious that a curved front source similar to that illustrated in the photograph of Fig. 5 in Part I of this article will give similar distribution to a strip, and, due to the larger surface, smaller spacing may be used and higher efficiency may thus be achieved. In such a case however, the diaphragm must be large compared to wavelength in both dimensions, because it is the nature of curved surfaces to become directional when the radius of curvature is comparable with the wavelength. When the diaphragm is large compared to λ it is impossible to design an intimate acoustic cross-over. This small inherent imperfection would appear to preclude its use in a “perfect” loudspeaker design, although its “efficiency” advantages will have obvious applications in some practical compromise designs.

Although designs free to the air on both sides have useful attributes, it is obviously desirable also to produce loudspeakers in cabinet form, enclosing the rear. This rear enclosure, if it is to be of reasonable size, will be the controlling factor for the diaphragm velocity, at least at low frequencies.

With any unit, the high-frequency limit will be set by efficiency requirements, and the low-frequency limit by amplitude limitation or by the compliance of the enclosure in series with the diaphragm compliance. This compliance will resonate with the air mass on the front and back of the diaphragm (unless the diaphragm is so large that the loading is ρc—for example, as in the curved diaphragms previously mentioned). Since the total mass is small, this resonance will usually occur above the lowest frequency of interest. It may be dealt with in two ways, (1) by adding acoustic mass within the cabinet to reduce the resonant frequency to the lowest required frequency, or (2) critically damping the resonant frequency and maintaining response below this frequency either by re-matching or by a secondary acoustic resonant circuit, or both.

There are innumerable ways in which either of these alternatives may be achieved. Consider the first alternative. Suppose that the enclosure is made deep and narrow (or fitted with partitions so that it appears deep and narrow to the loudspeaker): then, at wavelengths just under four times the depth, the reaction on the diaphragm will be positive. This will effectively force the resonance to the ¼ wavelength resonance of the depth of the enclosure. Absorbent wedges may now be fitted to control the resonance and to present

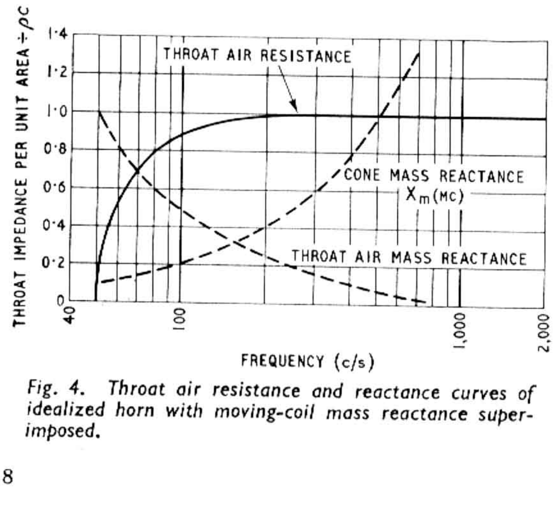
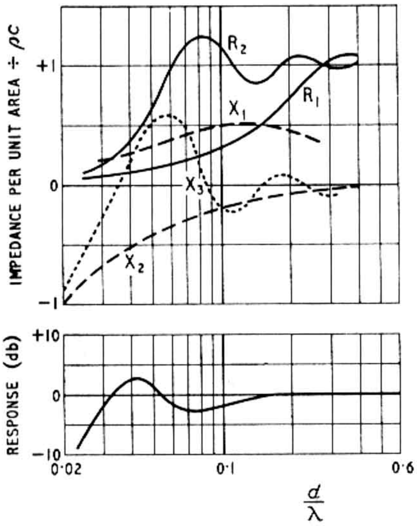


Fig. 4. Throat air resistance and reactance curves of idealized horn with moving-coil mass reactance superimposed.



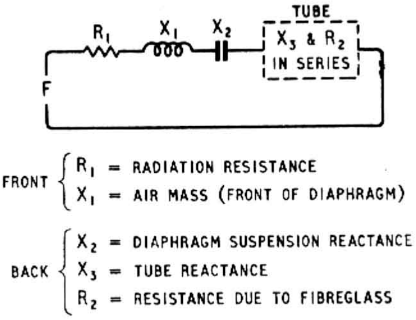


Fig. 5. Strip loudspeaker, long compared with wavelength, and of width d, *mounted in a wall, with the back of the diaphragm loaded by a tube with cross-sectional area equal to that of the diaphragm and of a length 5d, blocked at the far end. Resistance (fibre--glass wedge) included in tube to control impedance.*

a purely resistive load at all higher frequencies. Sound compression within the wedges becomes isothermal, decreasing the speed of sound, so that the depth of the enclosure can be reduced accordingly.

Fig. 5 shows the impedances of a strip unit loaded on this principle together with a curve showing the power output radiated as sound for constant applied voltage. The output is extended by more than an octave over that which would be obtained if the same volume of enclosure were allowed to act as a lumped capacitance.

Turning now to the second method of extending the low frequency range, Fig. 6 shows a diaphragm loaded by a capacitance leading through resistance and inductance into a larger capacitance. Both volumes have dimensions many times less than the wavelength in the ranges where they are operative.

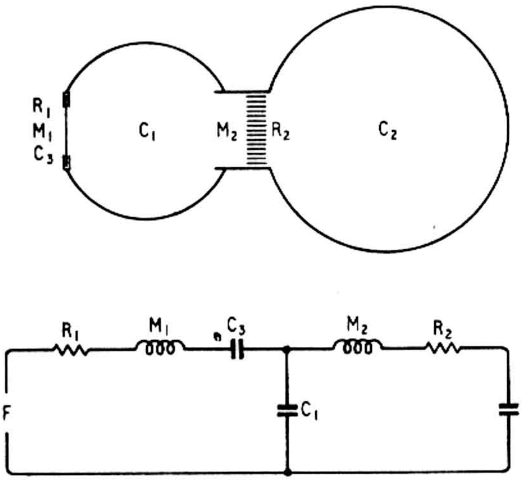
If the constants are adjusted to give a step in response as the frequency is lowered, then the total volume of the enclosure is reduced accordingly and the response restored to level by re-matching at the step frequency.

Fig. 7 shows a strip diaphragm loaded by a capacitance with series resistance, all elements continuing along the whole length of the structure. With this assumption there will be no waves in the enclosure along its length so that the constants can be calculated on a sectional element of thickness t. If the cross section of C_2 has dimensions which are many times smaller than the wavelength, then C_2 will behave as a capacitance (independent of length). If this proviso is not met then R_2 must be distributed to avoid C_2 appearing as a multi-resonant circuit.

Where the unit crosses over to another unit for low frequencies then R_2 may be adjusted to give a Q of 0.7 so that the cross-over components are already present in the acoustic circuit.

When the lower-frequency unit is arranged so that the two diaphragms are close and intimately coupled, then R_1 will be increased in value by the mutual radiation of the low-frequency unit. R_2 is then reduced to restore Q and we find that if R_1 is larger

Fig. 6. Diaphragm loaded by an equivalent capacitance C_1 leading through an acoustic mass and resistance M_2 and R_2 into a larger capacitance C_2.



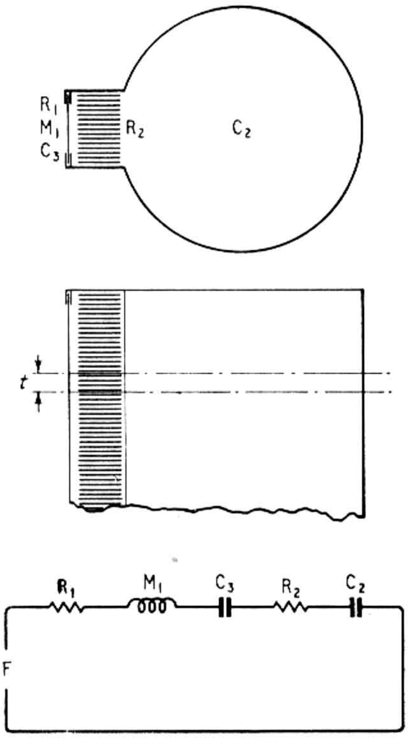


Fig. 7. In a long cylindrical structure the air column will be driven equally at all points along its length and no appreciable longitudinal standing waves can be established, at frequencies other than that corresponding to λ/4.

than R_2 a useful self-compensating effect takes place.

If the voltage applied to the low-frequency unit is reduced at cross-over due to tolerance in its cross-over components then R_1 is automatically reduced and the output of the higher-frequency unit increases at cross-over. At cross-over $P_{out} \propto \frac{R_1}{(R_1+R_2)^2}$

Where the enclosure of Fig. 7 is used for the unit covering the lowest part of the audio range, bass response may be extended by rematching or by introducing a secondary resonant circuit and utilizing back radiation from the diaphragm. If an aperture is provided at one end of the enclosure, opening to the air, then, when the enclosure length is ¼ wavelength, resonance will occur along its length, and there will be radiation from the aperture. 3/4, 5/4 resonances, etc., will not arise, because the enclosure is excited by a force distributed along its length. At frequencies above the ¼ wavelength, the enclosure will behave approximately as a capacitance, as if the aperture were not present.

The next part of this article will deal with electrostatic units as part of delay lines, and the application of various complete designs, " built in," " boxed in " and " doublet " in relation to the listening-room. Complete electrostatic loudspeakers can take several different forms, each of which in terms of frequency response, distortion and sound dispersion can meet a specification virtually to perfection. When the listening-room and subjective factors are considered it becomes impossible to lay down a rigid specification. To adopt a quotation " Each design is perfect, but some designs are more perfect than others "!

Acknowledgement. Fig. 2 is based on Fig. 5. 9, p. 127 of " Acoustics " by Leo. L. Beranek (McGraw Hill).

3—Complete Systems

Loudspeaker/Room Relationships

IN the first part of this article we showed that for a given size, the apparent efficiency of an electrostatic unit may be increased by reducing the bandwidth which that unit is required to cover. An obvious method of increasing the overall efficiency of a complete electrostatic system, therefore, is to divide the system into a convenient number of frequency bands and to feed them via crossover networks. Optimum design is obtained by increasing gaps and areas with decreasing frequency.

An alternative method of increasing apparent efficiency is to subdivide the loudspeaker area into a number of smaller units each covering the whole frequency range, the units being coupled by inductors so that the whole loudspeaker becomes a transmission line. (Fig. 1.) The acoustic radiation resistance appears as conductance in parallel with each capacitive element. For a fixed total area, and neglecting losses, the efficiency varies directly with the number of subdivisions.

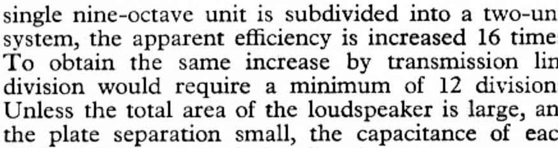


Fig. 1. Capacitive loudspeaker elements coupled with inductances to form a transmission line.

Consideration of these two systems shows that frequency division has considerable advantages over transmission line divisions for most complete systems of domestic size and power requirements. First, if a single nine-octave unit is subdivided into a two-unit system, the apparent efficiency is increased 16 times. To obtain the same increase by transmission line division would require a minimum of 12 divisions. Unless the total area of the loudspeaker is large, and the plate separation small, the capacitance of each section of the transmission line becomes very small indeed and requires correspondingly large inductance which must be of relatively high Q.

This apparent efficiency advantage of frequency subdividing over transmission line dividing holds until the bandwidth of each unit is reduced to two octaves.

Apart from transmission line subdivision applied to individual units of a frequency-divided system, practical consideration normally limits transmission line techniques to large-area diaphragms. When such is the case, however, additional facilities are available to the designer both in the accurate control of directional characteristics and in providing a constant phase contour, independent of frequency.

In discussing various possible forms of complete electrostatic systems, a novel situation arises. The quality criterion of a loudspeaker usually concentrates on three performance parameters, as measured in an unlimited atmosphere. (a) Ability to produce a required sound intensity over the audio spectrum with negligible non-linearity distortion. (b) The sound pressure over the designated listening area should be independent of frequency throughout the audio range. (c) Operation should be aperiodic.

Complete loudspeakers designed on the principles which we have been discussing are capable of meeting these three requirements to a new and exciting degree. We shall see that different designs and approaches differ not so much in terms of (a), (b) and (c) above, but in other factors of importance to quality reproduction; factors which have previously had to take second place or have been masked in the struggle for (a), (b) and (c).

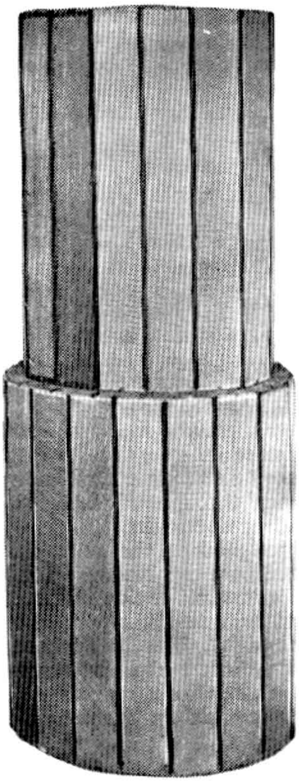
Corner Mounting

There has been a strong tendency in loudspeaker design to make use of the corner of a room. This is because at low frequencies the air load resistance for a given size of diaphragm is increased 8 times over that of an unlimited atmosphere.

Since the ratio of cabinet "stiffness" to air load resistance is independent of diaphragm size, any increase of resistance due to boundary walls and floors fundamentally reduces the size of cabinet required for a given performance.

As an example, the form of corner electrostatic loudspeaker illustrated in Fig. 2 and designed for full performance down to 40 c/s utilized an internal resonance with a Q of 3 and a built-in enclosure of 10 cu ft. Fundamentally the enclosure size could be reduced either by (1) increasing Q, (2) reducing power and apparent efficiency requirements, or (3)

Fig. 2. Wide-range electrostatic loudspeaker in a resonant corner enclosure.



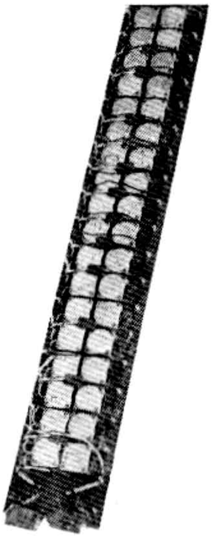


Fig. 3. Cylindrical electrostatic loudspeaker. Each strip carries the full frequency range and the sections are coupled to form an electrical transmission line. The inductor assembly is shown below.

restricting frequency range. Any one factor may be traded for any or all of the others.

It should be noted that with the diaphragm area of Fig. 2 the resistance could be substantially increased by reshaping the whole of the low-frequency area near the floor so that, with the boundary reflections, its dimensions laterally and vertically are similar. Such a form, with a suitably shaped treble unit above it, can be designed to give a level response in direct radiation to the listening area, so that the (a), (b), (c) requirements are not affected. Homogeneity on the other hand, due to the physical spacing of units, is destroyed. This may be more important than is generally realized, particularly in rooms of normal domestic size.

The high-frequency section (centre strip in Fig. 2) is sealed at the rear by an enclosure of width equal to that of the strip and incorporating a fibreglass wedge to offer almost pure resistance throughout the range of the unit. This sealing is necessary in order to maintain front air load resistance by preventing coupling between front and back.

Fig. 3 shows an entirely different form of corner design. The diaphragm area covers the whole surface and extends around the back to form an enclosed cylinder. Every part of the diaphragm carries the whole frequency range. The surface area is divided into units to form a transmission line. The total volume is 15 cu ft. The step in diameter is introduced because the transmission line rotates around the top portion and thence around the bottom portion. The time delay in the sound expanding from the top portion to the diameter of the bottom portion is equal to the time delay of the electrical voltages in the transmission line.

The complete assembly is placed a small distance from the corner of a room so that the boundary reflectors are aiding at the lowest frequency of interest. The large diaphragm area together with the boundary reflections provide a loading approximately equal to ρc at 30-40 c/s. Internally there is acoustic resistance treatment, so that there will be resistive loading at high frequencies, changing to a capacitive load due to the lumped enclosure at low frequencies. Simplified equivalent circuits for high and low frequencies are shown in Fig. 4. The turnover occurs at about 400 c/s and it is obvious that with constant voltage the response will be level above 400 c/s and drop at 6dB/octave below this frequency. This is corrected by progressively rematching to the amplifier below 400 c/s. The section shape may be elliptical to give a degree of direction at high frequencies.

It is obvious that the corner boundaries will introduce peaks and troughs throughout the frequency range. These are, however, exactly the same as occur naturally with live speech or music originating near boundaries in a room. To what degree these effects are important must at the present time be a matter of conjecture. It can safely be said that the subjective effect is by no means as alarming as the appearance of the response curve.

The advantage of a corner position has already been noted. This advantage is not gained without considerable detriment in other directions. If we wished to excite every room resonance to its fullest extent with a sound source of high internal impedance, we put this source in a corner because this is the position of highest impedance for every mode. In placing our loudspeaker in a corner therefore we are placing it in the *worst possible* position if our aim is smooth aperiodic sound.

Although the present trend appears to be to tolerate this state of affairs in the interest of the organ's 32ft rank (or reduction of cabinet size), the inherent smoothness of electrostatic loudspeakers once experienced is not lightly thrown away. and there is added impetus in attempts to improve the loudspeaker/room relationship.

Double Wall Enclosure

The strip "twin" unit design of Fig. 2 may be built into a wall in such a way that most room modes are not excited or are excited only feebly. If it is an outside wall, the rear enclosure may be added externally. If an inside wall it may spread over the wall so that from the appearance point of view it has virtually disappeared. Fig. 5 shows the general form of installation. The strip unit extends from floor to ceiling and the low-frequency sections are backed by 5in wide enclosures 4½ft in length, with fibreglass wedges incorporated. The impedances and response are shown in Fig. 5 (June issue). With the dimensions of this example, $d = 10$in since both 5in units are coupled, and the response will be within 3dB of 1 kc/s response down to 35 c/s. These figures include floor, one wall and ceiling, but do not, of course, include the effects of other room boundaries. Assuming a 2in thick wall for rigidity, the volume of a room of 300 sq ft floor area would be reduced by 2%.

There can be no initial excitation of floor to ceiling modes because vertical excitation is evenly distributed. Modes excited in a direction parallel to the wall on which the speaker is mounted will be reduced in number. Assuming a rectangular room, the number of modes excited will be some four times less than the number excited by a corner floor position.

As can be seen by the following summary, this form of loudspeaker leaves little to be desired.

1. The enclosure being "built-in" can be completely rigid.
2. The only fold in the enclosure is narrow compared to wavelength and being close to the diaphragm can cause no reflections in the range of that unit.
3. The loudspeaker and its enclosure are completely predictable.
4. The (a), (b) and (c) requirements previously mentioned can be met virtually to perfection.
5. Radiation throughout the whole frequency range is homogeneous; there is no source displacement and no phase problems at crossover.
6. Total radiated energy (as well as axial pressure) is independent of frequency.
7. The loudspeaker/room relationship is good.

Item 6 deserves further mention. The normal frequency response specification of a loudspeaker is in terms of sound pressure produced on the axis or over a limited listening arc. The mean spherical radiation (total power output) is not usually specified, although it will have a profound effect in a room because the intensity of indirect sound is dependent upon it. If high-frequency radiation is limited to a segment of, say, 90° × 30° (a typical figure) and bass radiation is hemispherical, and if the axis response is level, then there will be a step of 12dB in the mean radiated response. This produces an artificial step in the acoustic ratio (ratio of direct to indirect sound) producing unnatural hardening of the reproduced sound.

Doublet Sources

We now come to consideration of the doublet as a sound source and we shall see that it possesses properties of considerable significance in improving loudspeaker/room relationships. By a doublet we mean a diaphragm, radiating on both sides.

If we assume a 12in-15in unit (moving coil or electrostatic) mounted in a 4ft-5ft baffle, we find that the acoustic system has three main faults. (1) The acoustic air load falls to very low values at wavelengths larger than the baffle size. (2) The acoustic load is very irregular at low frequencies and (3) reflections from the baffle edge occur at higher frequencies. The second, and third faults can be mitigated by adopting peculiar shapes.

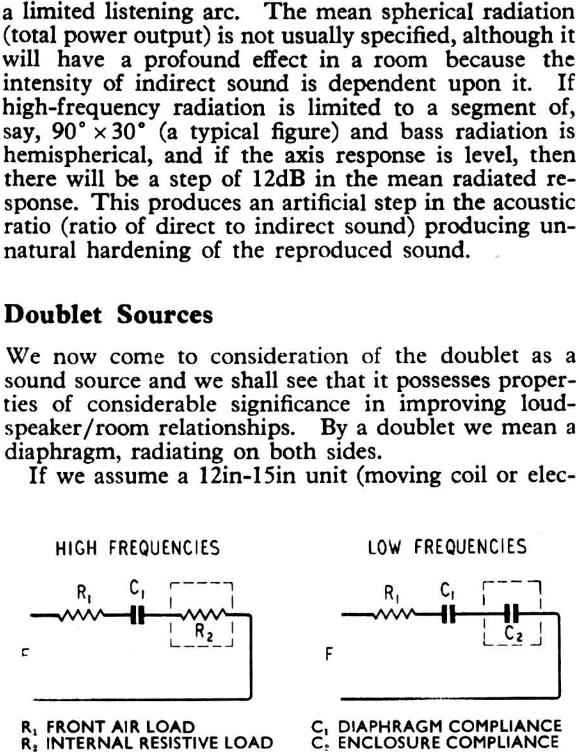


Fig. 4. Equivalent circuits at high and low frequencies of the acoustic loading on the loudspeaker of Fig. 3.

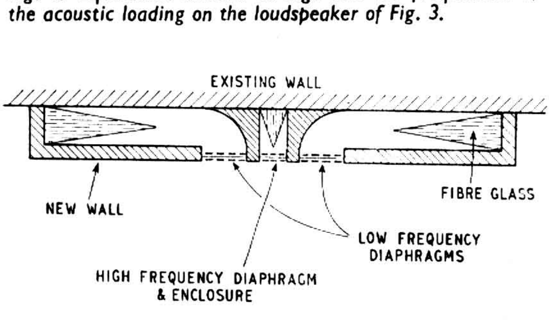


Fig. 5. Sectional plan showing one method of rear enclosure for a strip electrostatic unit.

If, instead of a baffle, we construct a composite electrostatic unit of the same area, the position is completely altered. The resistance per unit area and the total working area are both increased so that the air load is many times that of the baffle case. The load, and consequently the performance, is regular and predictable.

The construction is that of strip units progressively increasing in plate spacing and area from the centre line. Due to the air load resistances involved for each strip, the permissible bandwidth is reduced over that which could be obtained if the back radiation were sealed off and it is necessary to split the frequency range into three to obtain efficiency comparable to a two-way "sealed" system.

Any unloaded strip considered alone will have a resonant frequency when the diaphragm stiffness reactance equals the air load mass reactance. This is, however, placed below the frequency range of the strip, so that the mutual radiation of the adjacent strip carrying a lower frequency range increases the radiating area and *prevents the application of any effective mass*. The complete system is therefore entirely free of resonance except at one low frequency (usually placed at 30-35 c/s). The Q of this resonance is adjusted to maintain response to this frequency.

The complete loudspeaker has a cosine characteristic and this is substantially maintained through the range. It cannot radiate sound in the direction of its surface, horizontally or vertically, so that it cannot excite room modes in two out of the three room dimensions. It will only excite modes in the remaining dimension when placed at a region of maximum velocity for that mode. (The impedance looking into the loudspeaker is low.)

Having a "cosine" polar characteristic the mean spherical radiation is reduced by a factor of 3 at all frequencies, so that quite apart from freedom of mode excitations any colour due to the room is reduced by a factor of three. This is exactly analogous to a "velocity" microphone. In the same way that a "velocity" microphone is used in place of a "pressure" microphone to reduce studio colour, this "velocity" speaker will reduce colour due to the listening room.

Listening tests comparing "pressure" and "velocity" speakers of otherwise similar characteristics indicate that a velocity characteristic may well have important features for high-quality reproduction. An electrostatic loudspeaker of this type correctly positioned in the room meets all requirements as did the "wall" form previously described, with the addition of an even better loudspeaker/room relationship. The fact that it requires to be free standing well within the room may or may not be advantageous.

The more the acoustic ratio is reduced (provided always that it is reduced equally at all frequencies), the more one approaches the state of affairs that the pressure at the ears is a replica of the pressure at the position of the microphone in the concert hall or studio (ideal headphone conditions). It must be emphasized that many arguments for and against this condition have been proposed. It is outside the scope of these articles to enter these arguments other than to say that with a monaural channel the choice must be an æsthetic one.

A complete listening room can be designed to produce pressures throughout the room which are more or less equal to the pressures at the studio microphone.

A tube of small diameter compared to wavelength fitted with a piston at one end, and terminated at the other by a resistance of ρc will give pressures anywhere in the tube which are directly proportional to piston velocity and independent of frequency. Provided that the area of the piston equals the tube cross-sectional area, then the requirement of small diameter disappears.

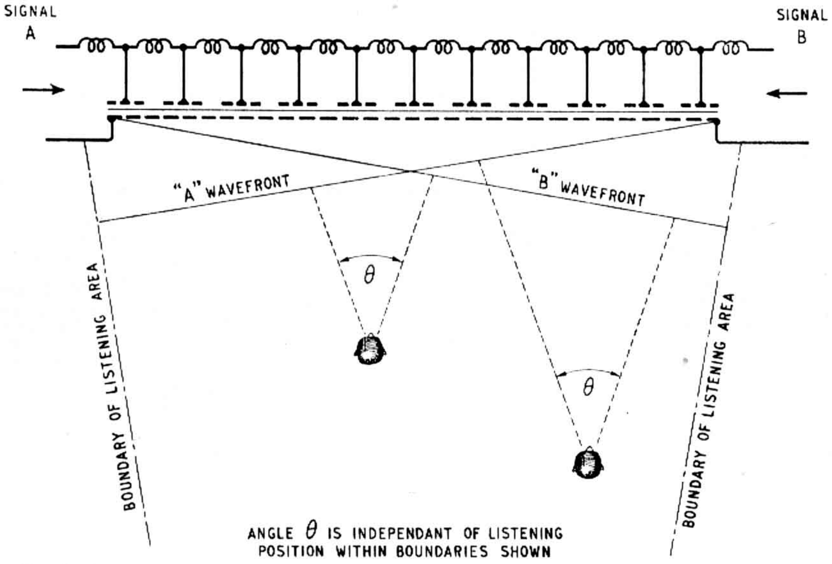


Fig. 6. Stereophony from a single transmission line loudspeaker, with separate channels feeding each end of the line.

A rectangular room with a diaphragm covering one wall and correct termination on the opposite wall meets the requirements. The space behind the diaphragm must be at least 10in deep and treated like the speaker in Fig. 3. The equivalent circuit is the same as Fig. 4. The sound absorption treatment of the opposite wall must ideally be several feet in depth.

Sound intensity throughout the room is independent of position (including the distance from the diaghragm). The apparent sound source is always in a direction perpendicular to the diaphragm and, of course, moves as the listener moves.

The same loudspeaker may be used for stereophony. With transmission line matching and feeding the signal at one end the wavefront will be tilted, due to time delay. Separate signals may be fed from either end to produce two tilted wavefronts, one for each signal. Since each apparent origin is perpendicular to its wavefront, the aspect angle from the listener is a constant and entirely independent of the listener's position over a large triangular area (Fig. 6). The relative intensity of the two signals is also constant.

A fixed angle, two-channel system of this type may be obtained with a less elaborate listening room. The strip arrangement of Fig. 5 may be installed horizontally instead of vertically. If each unit is a transmission line along its length, then two cylindrical wavefronts will be produced with exactly the same feature of constant aspect angle already described.

To summarize, the electrostatic principle is capable of surmounting the present limitations of other methods of drive. It is capable of overcoming the present tweeter/woofer concept to produce a closely coupled, integrated assembly. The problem of loudspeaker/room relationships (common to all loudspeakers) still remains, although the design versatility of the electrostatic makes it possible to design for optimum relationship if these can ever be defined for a monaural channel.

A closer understanding of the relative importance of the many factors involved are needed. (a) Source movement with frequency, (b) Homogeneity, (c) Acoustic ratio, (d) Mode excitation, (e) Phase contour, etc. All are factors which can only be tentatively assessed after long usage.

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