New Developments in Electrostatic Loudspeakers*

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Predicting the performance of a loudspeaker involves a large number of terms, some of which are only known for very simple shapes, and even these are only valid over a restricted frequency range. If a loudspeaker can be constructed with a sufficiently unrestrained and light membrane and with no other baffles or acoustical obstacles so that the whole is effectively acoustically transparent, then it can be shown by reciprocity that the transfer function reduces to a simple expression devoid of all complex and ill-defined impedances. Indeed, the acoustic pressure and phase at any point in free space can be determined from the simple measurement of the electric currents circulating in the transducer elements.

Electrostatic transduction for a loudspeaker has always had an appeal because there is very little mechanical impedance between the electrical forces and the acoustical load. One would intuitively expect the acoustic output to have a simple and direct relationship to the electrical input, and indeed experience shows that almost any electrostatic loudspeaker, however gross its other faults, will display a homogeneity of sound hard to achieve by other means.[1]

The forces available per unit area, at least for simple constructions and with air dielectric, tend to be small so that if the loudspeaker is large enough to produce adequate power at low frequencies, then directivity, interference patterns, efficiency, and other problems arise higher up the frequency range. Thus separate woofers and tweeters, acoustic lenses, curved surfaces, long strips, and other ingenious constructions have been proposed as solutions to the problem. Each of these adds its own complexity in either the mechanical or the acoustic parts of the transducer and detracts from the original simplicity, in most cases making accurate prediction of performance impossible. In this paper we suggest a new approach whereby a desired performance can be produced and controlled with a precision comparable to that of a good-quality ribbon microphone.

We tend sometimes to be slaves to past convention. Presented with the problem of predicting the performance of any loudspeaker, the approach is invariably to calculate the force on the mechanical system; to calculate the velocity resulting from this force acting on the combined mechanical and acoustical impedance; to calculate the radiation resistance and hence the power output, and so on. The result is formulas involving inertance, radiation resistance, and other terms which at best can only be calculated for extremely simple shapes, and even then their distribution over a surface is complex. It is hardly surprising that precision gives way to approximation, and detailed performance is unknown until models, perhaps involving costly tooling, have been constructed and measured.

But a refreshing simplicity arises if an electrostatic loudspeaker is constructed so that it is effectively acoustically transparent over the whole frequency range, that is, if immersed in any sound field it will not introduce discontinuities and will not disturb the field. When this is the case, radiation impedances and diaphragm velocities can be eliminated from the equations, and instead a much simpler relationship between electrical input current and acoustic sound pressure is revealed, even for complicated surface shapes.

We look first at the basic transduction mechanism and then by reciprocity derive the current–pressure relationships. Fig. 1 represents a section through an electrostatic loudspeaker of as yet undefined area. Of the

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[1] For a very full treatment of the electromechanical functions of electrostatic loudspeakers, see Hunt [1].

three electrodes, the two outer ones are assumed to be stationary plates, parallel to each other, and perforated to allow free passage of air. The center electrode (in practice a thin stretched membrane) is assumed to be sufficiently light and sufficiently unrestrained that if placed in any sound field, its normal vibrations will follow that of the air particles prior to its introduction. There are no baffles or boxes or other structural impediments.

The electrodes are open circuited, and the system is charged such that equal voltages E appear between the electrodes as shown. The electrical polarizing forces on the center electrode are in equilibrium, and no voltage appears across the outer electrodes.

Suppose now that the center electrode is moved, say to the left. The voltage on the left-hand side will reduce since with no charge migration it must remain in direct proportion to the spacing. The voltage on the right-hand side will increase, again in proportion to the spacing. The electrical forces on the central electrode are still in equilibrium, but now a voltage has appeared across the outer electrodes.[2]

For the present purpose all we need to note is that the two-terminal system is linear and the voltage appearing across the outer electrodes is directly proportional to the displacement of the center electrode.

Imagine a point source of volume velocity U in the far field at right angles to the plane of the membrane and at a distance r. Near our loudspeaker unit the waves from this point source will be essentially plane with a pressure of $Uf\rho/2r$ and hence an air particle displacement of $U/4\pi rc$ which is independent of frequency. The center electrode will vibrate in accordance with this displacement and will produce a voltage between the outer electrodes, independent of frequency.

[2] The fact that the electrical forces on the center electrode still cancel to zero means that no work has been done in moving the electrode from one position to another, and yet a voltage has appeared across the outer electrodes. This is not something for nothing, but merely a manifestation of a negative compliance. The mechanical system "sees" the capacity between the outer electrodes in series with a negative capacity of equal value. The practical requirement of a mechanical restoring force on the membrane can be ignored at this stage of our argument.

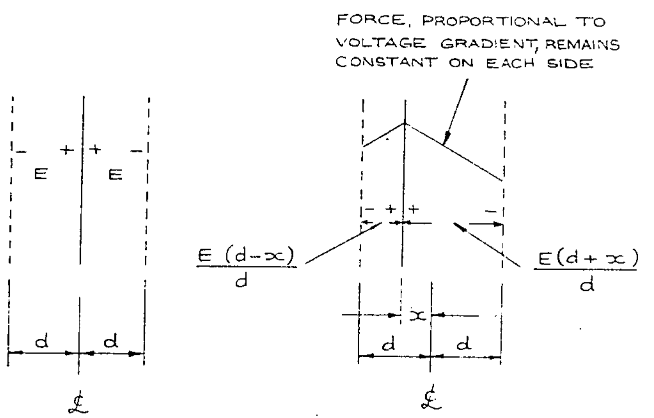

Fig. 1. Three electrodes—the open-circuit case.

We have a system in which a volume velocity at a point P produces a voltage at a pair of open-circuit terminals. We can conclude by reciprocity that a current into those same terminals will produce a pressure at point P equal to

$$\frac{E}{d} \cdot \frac{I}{r} \cdot \frac{1}{2\pi c} \quad [\mathrm{N/m}^{-2}]$$

where E is the initial polarizing voltage on the membrane when central, and $2d$ is the distance between the fixed electrodes. This then is the expression for the far-field axis pressure. The result, dependent on only two simple electrical measurements and two simple dimensional measurements, independent of frequency, area, or shape of the loudspeaker element, is in marked contrast with our usual experience in the field of loudspeakers.[3]

Because the expression is independent of area or shape, the contribution of each small part of the area is independent of any other area and solely defined by its local current. We can, therefore, subdivide the fixed electrodes and the currents fed to them in any way we choose, with the knowledge that we have only to substitute the vector sum of these currents in our equation to obtain the axis pressure. The pressure at any point off the axis is merely the sum of these small area currents with proper regard to phase shifts due to the relative distances from the point in question and the fact that each small area will have a cosine characteristic.

The performance of such a loudspeaker therefore can be described—and totally described—by the currents in its electrical circuits, real electrical circuits which, however complex, are amenable to adjustment, correction, and tailoring to a high degree of precision. (These real electrical circuits are not to be confused with circuit analogies of mechanical and acoustical systems.)

Armed with these simple relationships we can proceed to tackle more elaborate loudspeaker concepts with renewed confidence.

The maximum force on the membrane of a push-pull electrostatic loudspeaker ($\hat{F} = \epsilon_0 X^2 A/2$) is area dependent so that the normal solution to directivity of progressively smaller sources as the frequency increases is not available to us. 100 mW or so from an area of, say, 5 cm^2 at 10 kHz would require a pressure of some 500 N/m^2, several times greater than we can muster even if X, the dielectric strength of the air gap, can be increased by using very small air gaps [2]. Let us, however, assume an imaginary small source of adequate power output. We would have to recede only some 15–20 cm from its center to find air pressures well within the compass of an electrostatic loudspeaker system, and indeed an elec-

[3] The membrane will in fact vibrate in a complex pattern of maxima and minima in accordance with the distribution of the air load admittance. This does not affect our argument or the performance of the loudspeaker in any way, provided the polarizing charge is prevented from migrating along the surface of the membrane, each small elemental area thereby remaining a two-terminal network contributing to the far-field pressure in accordance with its local current.

trostatic loudspeaker system of sufficiently high compliance required to fulfill our criterion of acoustic transparency.

So perhaps we can recreate the sound pattern from an imagined ideal point source as it passes some boundary a little distance away from that source.

When sound passes from one region to another through some imaginary boundary, we can consider the boundary as acting as a simple radiator for the second region. If therefore we plot the air particle velocity normal to a plane dividing a source and an observer and if we then substitute a plane surface with the same velocity pattern, it follows—if the surface is large enough—that the same curved wavefronts would be reproduced. The observer would see a true picture of the source.

We can imagine a thin and flexible membrane with vibration patterns arranged to radiate waves as if they had come from a point source some little distance behind the membrane surface. We would perhaps expect that the membrane should vibrate in the form of radially expanding rings, falling in amplitude as they expand, in accordance with simple calculations. Certainly with an electrostatic system of annular ring electrodes connected as components in a delay line there is no great difficulty in distributing the force on the membrane in such a manner, and indeed diaphragm segmentation and signal distribution of this kind have been proposed at least as far back as Kellogg's patent of 1929 [3], and many variations have appeared since (see, for example, [4]–[6]).

However, a practical loudspeaker must be of finite area. If the area is limited, then the radial attenuation will not have fallen to zero, and there will be interference waves generated by the discontinuity. These will cause undulations in both the polar curves and the axis response, the latter being the more severe and the more localized if the membrane boundary is equidistant about the axis and the radial attenuation is small. In addition there will be a fall in response at low frequencies due to the "missing" radiation beyond the boundary.

These problems are common to all finite curved source radiators [7], and solutions call for frequency-dependent amplitude and/or delay shading [8]. But what would have been a rather formidable problem in a mechanical radiator is no longer so in our present case because all acoustical problems appear as electrical currents. The interference waves manifest themselves as reflections in a (now truncated) lossy delay line, and any steps taken by modifying this delay line to eliminate the electrical reflections will automatically eliminate the discontinuity waves.

Fig. 2 is an example illustrated by vectors. For simplicity the electrodes are divided into six sections of equal area and hence equal capacity. We assume delay and attenuation from section to section. The length of each vector is proportional to its local current, and the angle between each vector is proportional to the delay. Note that the axis pressure is represented by the vector sum of the currents, as shown by the dashed line, and obtainable directly, of course, by measuring I_{TOT}. At, say, twice the frequency the vector diagram will be something like Fig. 2(d). The current in the elements, and hence the lengths of the vectors, will increase and so will the angles. Again the axis pressure is shown by the dashed line.

To obtain the pressure at an angle θ off the axis, take the vector diagram for the frequency concerned and multiply the length of each individual vector by its directivity function. Thus if a particular vector is a narrow ring of radius a, then the new length will be

$$\frac{E}{d} \cdot \frac{I}{r} \cdot \frac{1}{2\pi c} \times \cos\theta \, \mathfrak{F}_0\left(\frac{2\pi a}{\lambda}\sin\theta\right) .$$

Add up the new vector sum as before.

A few calculations along these lines show that by optimizing the delay line we can produce smooth axis and polar curves together with an almost complete freedom of choice for the directivity index versus frequency. (The polar curves at wavelengths that are long compared with the loudspeaker dimensions must, of course, follow the usual dipole characteristic, and it is assumed therefore that an index of not less than 4.8 dB will be required at higher frequencies.)

The tacit assumption that an electrostatic loudspeaker can be made acoustically transparent at all frequencies must now be qualified. Near the low-frequency

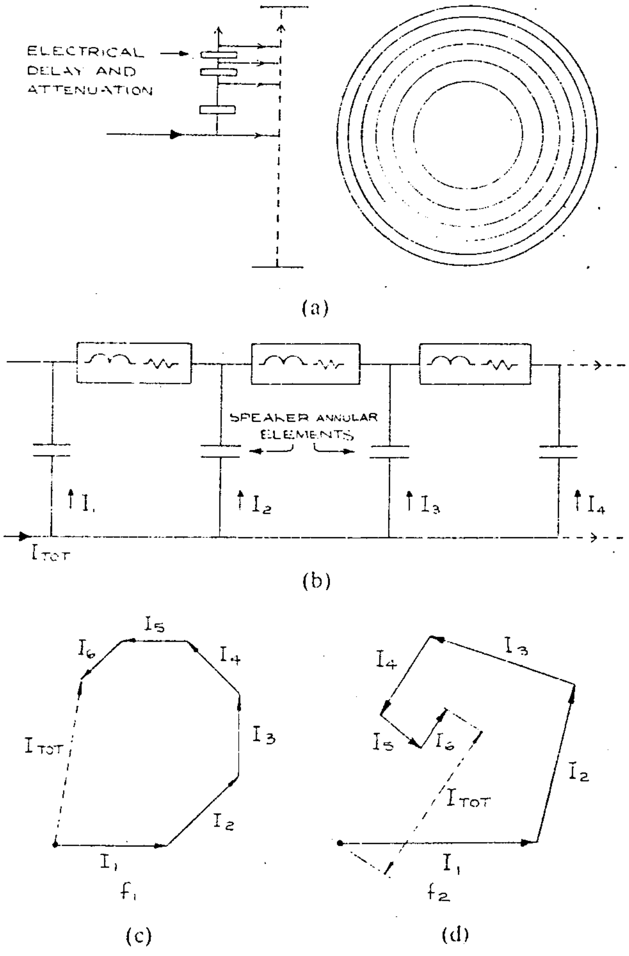

Fig. 2. (a) Radial delay and attenuation of signal currents. (b) Simplified electrical circuit. (c) and (d) Vector diagrams of far-field pressures.

resonance of the system the pressure will deviate from that given by the input current because of the suspension stiffness. If we could lump both the stiffness and the air load mass, the deviation would be that of a second-order high-pass filter centered on the low-frequency resonance of the loudspeaker with its terminals open circuited. But a stretched lightly damped membrane will vibrate in a series of modes so that no such simple assumption is possible and the success, or not, of the suspension design and its damping has to be revealed by other means. The solution is to examine the motional current because this is a direct measure of the membrane velocity ($u = I_{MOT}\, d^2 / \epsilon_0 EA$).

Fig. 3 shows a suitable bridge to extract the motional current. The so-called blocked impedance is obtained simply by switching off the polarizing supply since this has the effect of increasing to infinity the apparent impedances to the right of the dashed line. With the bridge carefully balanced, the polarizing supply is switched on and the membrane velocity for some three or four octaves can be plotted directly on a standard curve tracer. This motional current also gives us direct access for accurate distortion measurements and—by applying tone bursts—as a sensitive means of revealing any movement or resonance of the "fixed" electrodes. All these measurements can be carried out with the loudspeaker in an ordinary live and (moderately) noisy laboratory.

Fig. 4 shows a typical velocity plot. (The undulations at the higher frequencies are due to the loudspeaker hearing its own sound after reflection around the laboratory. This does not bother us because the effect of suspension stiffness and any mode effects reduce rapidly with frequency.) The motional current, of course, measures the membrane velocity averaged over the whole surface area and ignores its distribution. In the models tested, errors due to this effect are believed to be very small.

At high frequencies we must again expect deviation from the response measured by input current. The reactance of the diaphragm mass together with the effective mass of the air associated with the perforations of the fixed electrodes will no longer be small compared with the air load. We can make some reasonable calculated assumptions for these effects but—perhaps regretfully—we have to resort to acoustic measurements for confirmation.

Fig. 5 shows a practical example of these procedures, the low-frequency variation being obtained by direct measurement of the motional current and the high-frequency variations by calculation of the expected loss due to plate construction and diaphragm mass. The total electrode current is also plotted so that the sum of the three curves should give the axis response.[4] The actual response measured out of doors at 2 m—the nearest we dare go to maintain far-field accuracy—is shown in Fig. 6.

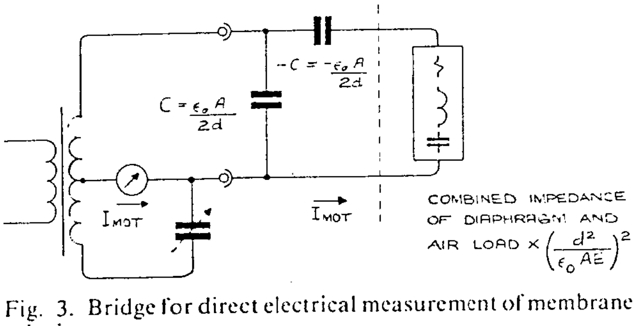

Fig. 3. Bridge for direct electrical measurement of membrane velocity.

CONCLUSIONS

(1) If a linear electrostatic loudspeaker is constructed as an acoustically transparent plane of uniform transduction with electrode currents separately accessible over the area of the plane, then the far-field axis response is simply and directly related to the vector sum of the electrode currents.

(2) The pressure at any angle off the axis can be derived by the summation of the currents for each elemental area with due regard to its doublet directivity function and its spatial relationship.

(3) The measurement of motional currents can give a

[4] The motional current conveniently measured with a stiff source includes the negative electrical stiffness −C whereas the true deviation from the simple current/pressure relationship will be due to the interaction of the air load with the unpolarized stiffness. The difference is exactly the same as the difference between the total electrode impedance with and without polarizing. Hence, in Fig. 5 it is the unpolarized electrode currents that are used in predicting the far-field pressure.

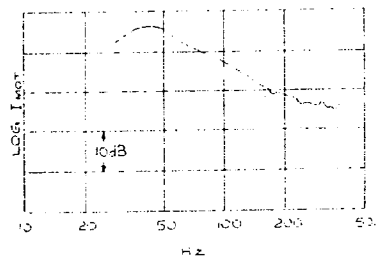

Fig. 4. Typical motional current curve for constant applied voltage.

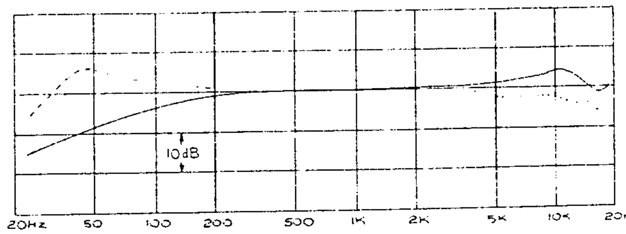

Fig. 5. Frequency variations and electrode current. ---- Deviation due to suspension stiffness from motional current measurements; —— Vector sum of electrode currents; ······ Calculated deviation due to diaphragm mass and plate obstruction.

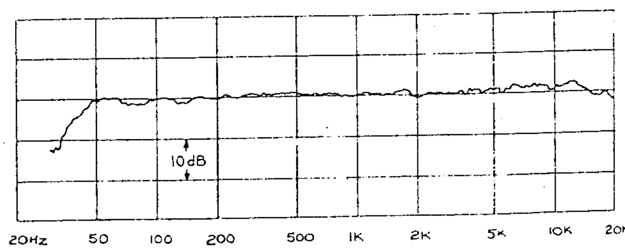

Fig. 6. Outdoor axis response at 2 m.

good indication, though not completely rigorous, of the deviation from simple current predictions at low frequencies.

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