An Overview of Electrostatic Speakers

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1. History of the Electrostatic Loudspeaker

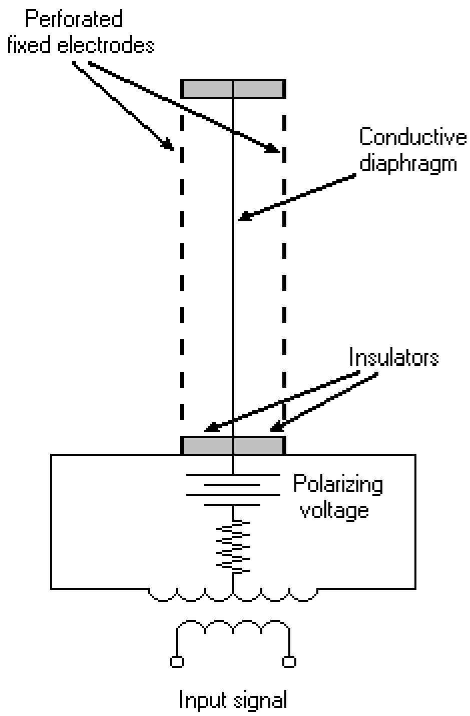
Given the recent stimulation of interest in the electrostatic loudspeaker (ESL), one would suspect that this type of speaker is a relatively new development. However, this is not the case; the appearance of electrostatic speakers even predates that of the more commonly found dynamic coil speakers, dating back to the early 1920's. It is known that condenser microphones have enjoyed a great deal of success since their introduction; why then, have these speakers—which operate on the same principle—taken so long to take root in mainstream audio application?

On closer inspection, we learn that these unique speakers were, upon their initial release, plagued by unwanted discharges, electrical breakdown, low efficiency, rapid oxidation of unstable structural materials, and difficulty in obtaining thin, manageable membranes—in general, there were serious issues and concerns regarding their reliability. With the introduction of the much more rugged and reliable dynamic coil loudspeaker in the 1930's, electrostatic speakers quickly became forgotten, taking a back seat to cheaper and more efficient alternatives. The problems associated with ESL's arose partially from an early, crude design, but moreover from a lack of quality construction materials and techniques. This remained the case until the 1950's, when discoveries of new materials, particularly that of polymer plastics, made possible the construction of more efficient and reliable models. In addition, new concepts of design evolved, seeking to take advantage of the full range of potential that electrostatics had to offer.

During this time, there was an increasing demand for the high-quality reproduction of high frequencies. Audiophiles seemed to be demanding a new, higher standard in the quality of reproduced audio signals. Electrostatic speakers, by way of design, are readily able to offer a faithful reproduction of high frequency content, and behave very predictably when doing so. This is very desirable, of course, as overtones and higher harmonics can contribute significantly to the overall timbre of the sound; this more precise imitation of the original recorded signal helps to make the audio emerge more realistically. These factors, in short, contributed to a revival of interest in the electrostatic loudspeaker. Unfortunately, this revitalization has never been fully realized as, while ESL's do excel at producing higher frequencies, the bass is difficult to reproduce and thus a more conventional moving-coil unit was always needed anyways; also, the cost of producing these devices has always put them out of reach of most consumers.

2. How they work

The basic design of an electrostatic loudspeaker consists of a very thin plastic membrane ($1/10^{th}$ the thickness of a human hair) suspended between two electrodes. The membrane is electrostatically charged with a high DC polarizing voltage, while the electrodes are fed with ground potential. Typical polarizing voltages are usually in the order of 2000 – 3000V. When there is no signal, the diaphragm remains suspended at equal distances between the two electrodes. If a voltage is impressed upon the primary coil of the transformer, a positive voltage appears at one electrode, while an equal, yet opposite in polarity, voltage appears at the other. Since like charges repel and opposite



charges attract, the diaphragm will be attracted to one side, while pushed away from the other. This arrangement is called a 'push-pull' configuration. If an audio signal is sent to the transformer instead of ground potential, an electromagnetic field will be created which varies in response to the changing voltage of the audio signal. The diaphragm can then be made to move back and forth in this field, consequently mimicking the changes in the input signal. Finally, both electrodes are perforated, so that they seem 'acoustically transparent,' thus avoiding pressure effects of trapped air and also allowing acoustic energy to move away from the diaphragm.

Two methods of constructing electrostatic speakers have emerged. The first involves stretching the diaphragm over a frame, supporting it at its edges, and leaving the middle unattached and free to vibrate. The second method, which is much less common today then it was in the 1950's and 60's, uses an "inert diaphragm" supported by several tiny elements equally spaced across its surface. These spacers hold the diaphragm in the centre between the electrodes, yet more importantly allow the diaphragm to be curved without seriously impeding its ability to vibrate. This capability of curving the diaphragm is an important tool in controlling the directionality of radiated sound, as discussed later.

2.1 Details of operation[1]

The first item to understand is the forces at work in an electromagnetic field. A charge, Q, placed in a field of strength $V_{sig}/2d$ will experience the following force:

$$F = Q \times (V_{sig}/2d) \qquad \text{(a)}$$

where F is the force (N) experienced, V_{sig} is the signal voltage, Q is the strength of the charge (C), and 2d is the distance between each electrode (d is then the distance between the diaphragm and one electrode—this simplifies things later).

This is adequate for small charges, but the polarizing voltage on the diaphragm is huge by comparison, so more detailed analysis is necessary. Let's assume the total charge on the diaphragm will not change once it has reached equilibrium—the large resistance placed in series with the polarizing voltage helps prevent any discharge. Furthermore, by examining the simple schematic above, it should be obvious that there is an inherent capacitance present between each plate and the diaphragm. The total capacitance[2] will vary as the diaphragm moves, increasing as it strays farther from equilibrium. Therefore its voltage must fall, as given in the fundamental equation:

[1] This section assumes an ESL with flat plates, of the 'push-pull' design.
[2] $C_{total} = (C_1 \times C_2)/(C_1 + C_2)$ is not included above as it seems straightforward…

$Q = CV_{pol} = \text{constant}$ (b)

where Q is the total charge (C) between the electrodes and the diaphragm, C is the total capacitance (F) of the system, and V is the polarizing voltage (V). Since Q will essentially remain constant, it follows then, that C and V will vary in an inverse relationship to each other. The capacitance of a parallel plate air-dielectric capacitor is given by the formula:

$C = \_{0}A/d$ (c)

where A is the area (m^2) of the plates, d is the distance (m) between them, and $\_{0}$ is a constant equaling 8.854 x 10^{-12} F/m. If we take the above result and, using equations (a) and (b), we can find the force which is created by the signal voltage; this result is independent of the diaphragms' position from equilibrium:

$F_{sig} = \_{0}AV_{pol}V_{sig} / d^2$

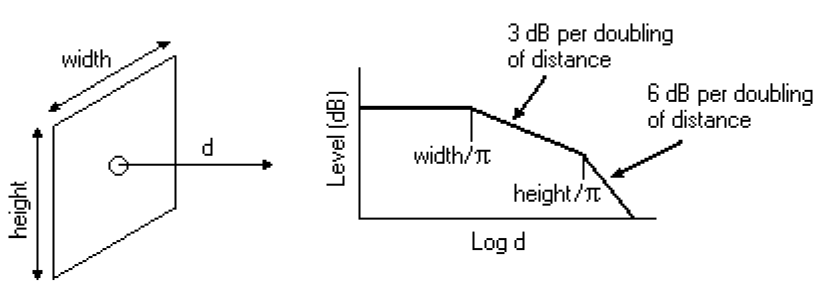
Where F_{sig} is given in Newtons. So now we have an equation which relates how much force acts on the diaphragm given a certain input voltage. Typical forces for a 1.3m x 0.7m diaphragm with a 2mm gap, a polarizing voltage of 3kV, and a signal voltage of 2kV peak (very roughly approximating any ESL…) are in the range of 12 N.

The above analysis neglects any loss of charge which the diaphragm may incur, it also neglects the fact that the force will vary according to the diaphragms' position between the plates. However, this can give us a general idea of what is going on in an ESL, and what forces are at work.

3. Performance related issues

3.1 Radiation

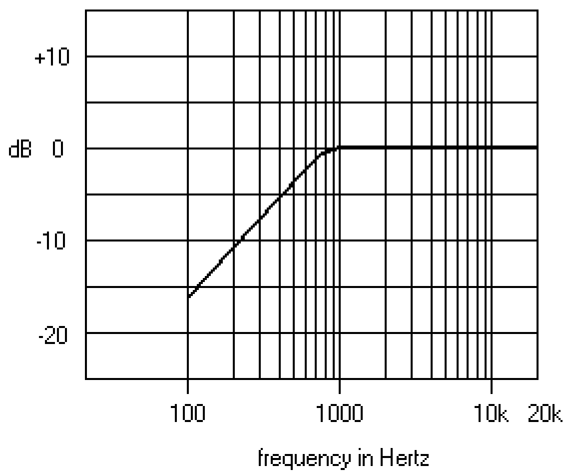
Single cones and domes can be said to behave effectively as point sources, in that the sound level they produce will drop by 6 dB for each doubling of distance away from the driver. However, the attenuation with distance from a planar source exhibits quite a different response. There is no decrease in the level until a distance of width/ π has been reached (see diagram, next page), at which point a –3dB per doubling of distance is noticed. It is not until a distance of height/ π is reached that we find the common –6dB decrease. The diaphragm of an electrostatic speaker is essentially an unbaffled piston, and behaves much like as described above. In the data shown, transitions occur abruptly; however, in the real world there would be a more gradual transition between sections.



Room conditions will affect the strength of the measured sound, too. Reverberations and can cause little attenuation in the listening space, which may complicate stereophonic reproduction. Controlling the directivity of the sound (discussed later), however, has had positive results in the quality and realism of stereo imaging.

3.2 Frequency Response

In general, the frequency response of a simple ESL can be observed below. Bass frequencies fall off at a rate of 6dB/octave, while there is a flat response for higher frequencies. Traditionally, ESL's have been paired with moving coil sub-woofers to compensate for the loss of bass, but recently new, full-spectrum designs have made this unnecessary.



TYPICAL FREQUENCY RESPONSE 4 FT. ON AXIS

The uppermost frequency limit is restricted primarily by the high current demands which the speaker places on the amplifier. Since the loudspeaker load is primarily one of capacitive reactance, there can be great amounts of current drawn at high frequencies. (Recall that: V = IR; V is kept constant, and R_{cap} will decrease at high frequencies, therefore I must increase).

One unfortunate deficiency which electrostatic loudspeakers possess is a natural inability to reproduce low frequencies. The limiting factor in producing low-end is the 'excursion capability' of the diaphragm. First, we must consider that the wavelength increases as the frequency decreases. So, in order to recreate bass frequencies, the diaphragm must be able to move a greater amount of air than it has to for higher frequencies. This can be accomplished in two ways: either we make the size of the diaphragm greater, or we allow it to have a greater degree of freedom in its amplitude as it vibrates. Both options have drawbacks, however. By making the membrane larger, we incur very irregular high-frequency directional control, but more importantly, there are feasibility limits as to how large we can go. Allowing the diaphragm more leeway to move is also not a viable solution because the gap between the diaphragm and electrodes must remain small. Otherwise, there will be insufficient attractive and repelling forces to move the diaphragm accurately, thus causing a loss of clarity in the higher frequencies.

Therefore, it is customary to construct ESL's using several diaphragms, or panels, of different sizes. Narrow, vertical panels used for the highest frequencies are placed next to larger ones for the middle and lower frequencies. By varying the size and tension of the diaphragm, these panels can then be optimized for a certain frequency range. The result is a smooth response, as each panel still operates as a full-range driver, but being optimized for a specific frequency range. Moreover, each radiating panel is proportional in size to the frequencies it will be radiating, thus having an effect over the dispersion of said frequencies (as discussed below). Finally, since each diaphragm acts as a full range driver (but optimized for a certain range), there is no need for a crossover[3] (although some systems still use them) and problems with phase distortion do not arise. There are no discontinuities in the frequency response curve, and we get the full music spectrum, as it was recorded. A variation on the above design is to use a crossover to filter out mid- and –high frequency content on the largest panels, and high frequency content on medium size panels. In this way, the entire radiating surface is used for the bass, with less area devoted to the midrange, and even less for higher frequencies. The result is that the levels of the different frequency ranges will be more carefully balanced, and the presence of the bass can be more readily heard[4]. Other strategies include setting the resonant frequency[5] of each panel at a slightly different bass frequency, thus achieving peaks in the bass with the equivalent input voltage.

Another advantage of a system of panels is that there is a reduced capacity per section. This reduces the destructiveness of a spark should a spark occur between the electrodes. With a large capacity charged to a high potential, a spark may readily be hot enough to burn a hole in through the diaphragm, while with smaller panels a much less intense spark occurs for the same voltage. Also, the overall sound will not be affected as other panels will continue to radiate while the one afflicted recharges.

3.1.1 Directivity

Electrostatic loudspeakers offer new possibilities in controlling the directivity of sound; indeed, much of the appeal of these speakers stems from their unique radiation properties. As we learned earlier, there are two methods of going about constructing ESL's: with a curved diaphragm, or simply with a flat diaphragm.

The curved diaphragm methodology was the first and earliest approach to controlling radiation patterns. As we should recall, a flat radiating surface which is large compared to the wavelength of the radiated sound becomes increasingly directional. That is, until we curve the plane in the horizontal direction. A curved radiator of this type is observed to give an even dispersion of high frequencies—all the way to the end of the reproduced spectrum—over an angle of 55°. In the vertical direction, the radiator remains flat, and so radiation occurs at 90° from the diaphragm up until the height of the speaker. Thus, by controlling the radius of curvature in the horizontal plane and the vertical height of the diaphragm, speaker manufacturers can control the dispersion pattern to fit any area. This method is not so popular today and ESL's are now rarely produced this way. The principle drawback is that this system is not of the 'push-pull' type which otherwise predominate today; rather, only one electrode is used to 'push' while the mechanical restoring force of the diaphragm returns it to its original position. In short, high frequency content suffers and the maximum level is considerably less than with two electrodes because there is less force acting on the diaphragm.

With the more common flat-panel systems, advantage is taken of the size of the radiating surface. A radiator which is large compared to the wavelength of the radiated

[3] The "Quad 989," for example, has no crossover

[4] Full-range speakers such as the "Emperor" are able to generate over 120dB of acoustic pressure from 30Hz—45kHz, and 100dB at ultra-low frequencies of 15-20Hz; they use a crossover, however.

[5] $T = M(f \times a \times b)^2 / 0.146$, where T = tension, M = mass of diaphragm, a and b = dimensions of the diaphragm, and f = fundamental frequency.

sound becomes increasingly directional (such as the membrane in an ESL). Therefore it is common to construct ESL's as described above, with several panels of different sizes. Varying the size of each panel enables one to accurately control the directivity of the sound. Larger panels will beam high frequency content, while smaller panels will evenly distribute it. So, with a clever design using various shapes of panel, it is possible to get frequencies to disperse evenly.[6]

3.4 Efficiency, Impedance (acoustic, electric)

In theory, the efficiency of an ESL is very high because there are very few things which can weaken the signal power. Of the few things which can, however, is the air-load resistance (which represents the useful audio output, anyway). This acoustic impedance can vary over the surface, becoming more mechanical in nature as one approaches the clamped edges. While the mass of the diaphragm, given its extremely thin cross-section, can be neglected, it is a common misconception with ESL's, that their *moving mass* is extremely small. There is a layer of air directly associated with the diaphragm which is estimated to be about five times greater than the actual per-unit mass of the diaphragm itself.

The electrical impedance which ESL's present to an amplifier varies with frequency since these speakers are nothing but large capacitors. As the frequency increases, the impedance decreases by 6dB per octave. (I increase, Z or R decreases…, P? => P = VI = I2R) …however, demands more current at high f, so P = VI means power usage increases at high f.

Power requirements also increase with the size of the diaphragm. A 35W valve amp, or a 50W tube amp are sufficient for a few speakers, with most others requiring around 100W.

3.5 Power Output

The maximum output of an electrostatic loudspeaker is proportional to the maximum strength of the electrostatic field generated between the diaphragm and the electrodes. This value is the sum of the polarizing voltage and that of the peak signal voltage which is applied to the electrodes. As this total value becomes too large, however, the dielectric breakdown of air occurs between the diaphragm and the electrodes. To avoid this, manufacturers will set the polarizing voltage plus the maximum intended signal voltage to be slightly less than the breakdown of the air itself. In terms of the maximum force which can be generated, the following equation is given:

$$F = (u^2/16\pi)(1.11 \times 10^{-5})\ \text{dyn/cm}^2$$

where F is the force per unit area, and u is the maximum electrical field strength (V/cm) before the onset of air ionization. In terms of acoustical pressure:

$$P = I_{sig} \times V_{pol}/2\pi crd$$

[6] Some manufacturers, such as "InnerSound," prefer to have very narrow dispersion; others, such as "Quad" and "Martin-Logan" have very wide dispersion.

where I_{sig} is signal current sent to the plates (A), V_{pol} is the polarizing voltage, c is velocity of sound, r is the measuring distance (m), and d is the space between the diaphragm and the electrode. P is in N/m^2.

The maximum output of most ESL's is still not as great as the average dynamic-coil design. Luckily, advances in design have greatly increased the maximum possible volume level over levels of 40 years ago—maximum levels of 120dB are rare but not unheard of.

4. Advantages over conventional speakers

Now we come to some of the electrostatic speakers' many advantages. (This will probably read like an advertisement because I've been swept up in the propaganda I've been exposed to while researching these things…) The first and most apparent benefit is its reproduction of high frequency content. The response of the lightweight diaphragm is in every way superior to the heavy moving coil. Recall that the moving part of a magnetic speaker is relatively substantial—its voice coil, suspension system, and cone add up to a lot of mass. The total weight of all of these parts is much more than the air that the speaker drives, and since music consists mostly of transients, the mass of magnetic speakers prevents them from responding quickly enough to follow a rapidly changing waveform with perfect precision. We know that the mass of an electrostatic loudspeakers' diaphragm is quite small and can, as a result, respond near-instantaneously to the audio signal. This is not to say that transient response is 'perfect,' but when compared to the moving coil, the difference is readily discernible.

Another attraction of ESL's is that the diaphragm can be a full frequency driver. This means that no crossover is necessary, or that the crossover frequency is quite low if other methods are employed to strengthen the bass. Either way, coloration from phase distortion in the higher frequencies is removed.

The diaphragm in an ESL, for the most part, moves evenly over its entire surface (movement varies as we progress from clamped at the edges to more free in the middle), whereas the voice coil of a magnetic speaker drives only one point—the apex of the cone. Cones are designed to not be perfectly rigid—different parts vibrating at different frequencies—so the driven surface flexes and distorts, consequently distorting the sound. The advantage which ESL's have here is that 'breakup' is eliminated, removing another coloration of the sound which is familiar to ordinary moving-coil systems. Also, because the diaphragm moves more equally as a unit, it has virtually zero distortion[7], so their sound quality remains high, and they produce a unified, coherent wave-front for precise holographic-quality imaging.

Of the many potential pitfalls in the accurate reproduction of an audio signal, resonance is something which poses few problems for the ESL. Changing the tension of the diaphragm enables manufacturers to control which frequencies the ESL will resonate at. Usually this value is set below 100Hz, meaning there are no high frequency resonances. A magnetic speaker resonates at many frequencies, behaving somewhat like a bell. Also, because the "ringing" continues long after the original note has stopped,

[7] Nonlinear distortions are below 0.1 - 0.05%, comparable with the distortions of a good amplifier.

transient response is poor. And finally, ESL's don't need a cabinet. All those problems associated with cabinet design can be circumvented.

All this, in short, frees the electrostatic loudspeaker from limitations which plague conventional systems. Coloration and non-linear distortion which are associated with most speaker systems is removed. Indeed, we are so used to hearing the 'colour' which the moving-coil loudspeaker introduces that we have grown to accept it. Certainly, hearing the 'uncolored' version will come as a revelation. And while there still exist problems with ESL's, (sure, they're still expensive and big) they have overcome many other limiting factors which have existed since their resurgence of popularity in the late 1950's. With further developments in materials, cheaper polymers, and ongoing research, these types of speaker are sure to start showing up with more frequency.[8]

[8] Pun intended.

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