# DISTORTION IN

# Electrostatic Loudspeakers

## CONDITIONS NECESSARY FOR LINEAR OPERATION

AFTER holding undisputed supremacy for a quarter of a century the moving coil principle of drive for loudspeakers must now meet growing competition from the electrostatic principle, which has been shown to be capable of intrinsically better performance from the point of view of non-linearity distortion.

**Basic Formulæ**

$$Q = CV = \frac{\kappa AV}{d}$$

$$C = \frac{\kappa A}{d}$$

$$V = \frac{Qd}{\kappa A}$$

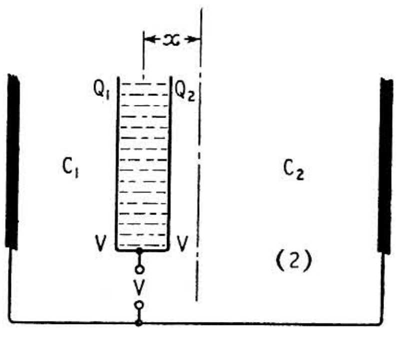
$$F = \frac{QV}{2d} = \frac{\kappa AV^2}{2d^2}$$

Recent articles [1, 2, 3] have reviewed the theoretical basis and given some pointers to the practical requirements for the realization of low distortion levels. The material presented was voluminous and to those readers who remember the Vogt loudspeaker[4] of the late '20s may not have seemed to include any new feature. Like the latest designs it operated on the push-pull system with a polarizing voltage applied through a resistance to a thin diaphragm supported midway between perforated metal plates, to which the signal was applied "differentially" (i.e., in push-pull).

This form of construction gave a marked improvement over the single fixed plate electrostatic loudspeaker, but non-linearity due to the increased force as the diaphragm approached either of the two fixed plates was acknowledged and to some extent compensated by adjustment of the elasticity and diameter of the diaphragm.

This non-linearity arises because the force acting on the diaphragm, which is always zero in the mid position, increases when the diaphragm is displaced —except in one particular set of circumstances, which we shall discuss later. The displacement need not be due to the applied signal voltage and can be mechanical. It is, in fact, convenient at this stage to forget the effect of the signal and to concentrate only on the stability of the diaphragm under the influence of the polarizing voltage alone, for if there is a non-linear force already in action the signal can only add to it.

Some useful basic electrostatic formulæ are given in the accompanying panel, and if we apply them to the four diagrams we should be able to see why some electrostatic loudspeakers distort and others do not. The formulæ assume the use of rationalized MKS units and that $\kappa$=total permittivity of the space between electrodes, A=area of electrodes,



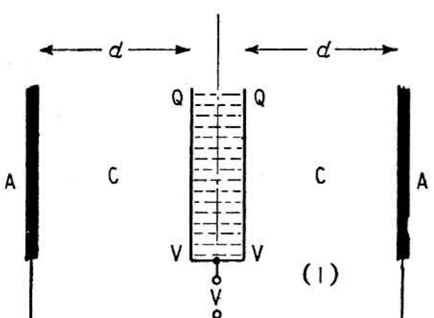

$$F = \frac{\kappa AV^2}{2(d-x)^2} - \frac{\kappa AV^2}{2(d+x)^2} = \frac{2\kappa AV^2dx}{(d^2-x^2)^2} \qquad Q_1 = \frac{\kappa AV}{(d-x)} \qquad Q_2 = \frac{\kappa AV}{(d+x)}$$

*(2) Conducting diaphragm, directly connected and displaced from mid position*

C=capacitance, Q=charge, V=voltage and F=force. The thickness of the central diaphragm has been exaggerated so that the existence of conductivity between the two surfaces can be shown by horizontal shading.

Diagram (1) represents a diaphragm exactly centred between the fixed plates with a polarizing voltage V, which will be the same on both sides, since the diaphragm is a conductor. The capacitance on both sides is the same, so the charges will also be equal. While the diaphragm remains central it will experience no resultant force.

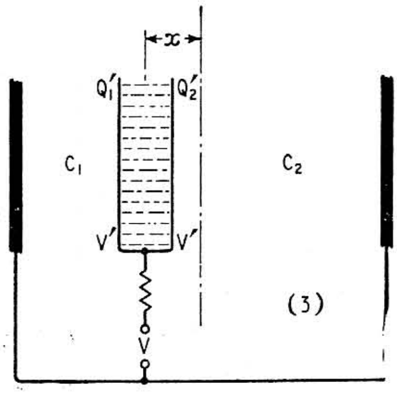
In diagram (2) the diaphragm has been displaced a distance $x$. Both faces are still at the same potential, but the capacitances on each side are unequal and there must be a redistribution of charge. There




$$F = \frac{\kappa AV^2}{2d^2} - \frac{\kappa AV^2}{2d^2} = 0$$

*(1) Conducting diaphragm, mid position, directly connected*

[1] A. A. Janszen, *Journal Acoustical Engineering Society*, Vol. 3, No. 2, April, 1955.
[2] P. J. Walker, *Wireless World*, May, June, August, 1955.
[3] H. J. Leak, *The Gramophone*, May, 1955.
[4] *Wireless World*, 12th September, 1928, p. 309 and 29th May, 1929, p. 553.
[5] *Wireless Engineer*, May, 1955, p. 119.




$$\kappa AV'\left(\frac{1}{d-x}+\frac{1}{d+x}\right)=Q'_1+Q'_2=2Q$$

$$V'=\frac{2Q}{\kappa A\left(\frac{1}{d-x}+\frac{1}{d+x}\right)}$$

$$F=\frac{\kappa A}{2}\left(\frac{1}{(d-x)^2}-\frac{1}{(d+x)^2}\right)\frac{4Q^2}{\kappa^2A^2\left(\frac{1}{d-x}+\frac{1}{d+x}\right)^2}$$

$$=\frac{2Q^2x}{\kappa Ad}$$

*(3) Conducting diaphragm, displaced and fed through a high resistance (constant total charge)*

is a resultant force on the diaphragm which does not vary linearly with the displacement *x*.

So far we have assumed that the conducting diaphragm is directly connected to the polarizing source and that current can flow to make up the change of Q necessary to satisfy the equation Q=CV when V is kept constant and C is changed. Under these conditions $(Q_1+Q_2)$ will never be less than 2Q.

If a resistance is inserted between the source and the diaphragm it will not affect the conditions (2) if the time constant it forms with $C_1$ and $C_2$ is short compared with a half-cycle of the applied signal; this condition is satisfied by the values which were used for safety resistances in the early electrostatic loudspeakers.

When the series resistance gives a time constant long compared with a half period of the lowest audio frequency the charge on the diaphragm cannot change appreciably from its average value $(Q_1'+Q_2')\approx 2Q$, so when displaced the potential of the diaphragm must fall to a new value V′, diagram (3). But, and this is the important point, the charges on each side of the diaphragm will still be dissimilar; and, although we are now working under "constant total charge" conditions there is still a force due to the polarizing voltage when the diaphragm is displaced. This force is linear with displacement, but is not due to the signal and is, therefore, a distortion.

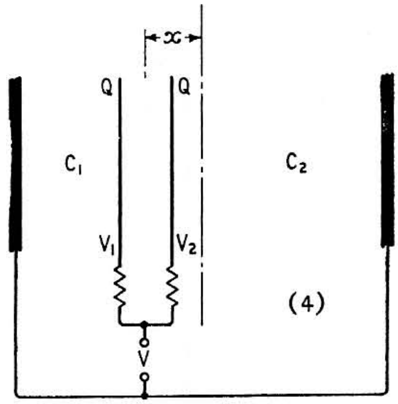
W. T. Cocking has shown[5] that all unwanted forces will disappear only when the two faces of the diaphragm are insulated from one another. Under these conditions, with no possibility of migration of charge as the result of the changes of capacitance, and with separate high resistors feeding each side of the diaphragm, it will be the potentials $V_1$ and $V_2$ which will accommodate themselves to satisfy Q=CV. With voltage varying directly with electrode spacing we now have exact compensation and there will be no force due to the polarizing voltage, irrespective of the position of the diaphragm, (4).

Having disposed of the forces both linear and non-linear arising from the presence of the charge itself, the force due to the establishment of an additional signal field between the two outer fixed plates may be considered separately and unhindered. This is simply the product of the charge and the field strength due to the signal and is independent of the position of the charge in the field.

The object of this note has been to point out that a series resistance will not by itself linearize the electrostatic loudspeaker; the diaphragm must be an insulator so that the migration of the charge between faces is prevented—at least for the duration of a half-cycle of the lowest frequency to be reproduced. If the surfaces of the diaphragm are sprayed to make them conducting, the polarizing voltage must be fed through separate high resistances to each side. A simpler practical approach would seem to be to leave the diaphragm uncoated and rely on the surface resistivity being high, but not as high as the bulk resistivity of the material.

When the electro-mechanical driving force has been linearized there still remain a number of problems for the designer, but they are far less onerous than those associated with the moving-coil drive. The light mass of the electrostatic diaphragm implies much less internally circulating energy in the form of momentum. The load is predominantly that due to the acoustic radiation resistance and the mechanical reactive component is negligible. Good transient response should therefore be easier to achieve, and because the diaphragm is being driven over the whole of its surface, variations due to "break-up" of the vibrating surface—a feature inseparable from coil-driven cone diaphragms at high frequencies—are negligible.

The only remaining problems are how to ensure adequate air loading at very low frequencies and how best to match the capacitive electrical impedance to the amplifier.




$$V_1=\frac{Q(d-x)}{\kappa A}\qquad V_2=\frac{Q(d+x)}{\kappa A}$$

$$F=\frac{\kappa AV_1^2}{2(d-x)^2}-\frac{\kappa AV_2^2}{2(d+x)^2}$$

$$=\frac{Q^2}{2\kappa A}-\frac{Q^2}{2\kappa A}=0$$

*(4) Insulating diaphragm, displaced, with conducting surfaces separately fed through high resistances*