The Electrostatic Loudspeaker

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Construction and characteristics of the new capacitance-type high-frequency loudspeaker developed by Philco and used in the company's receivers.

During the past 30 years there has been continuing progress in the art of recording and reproducing music and speech with the ultimate goal the ability to recreate the original performance with complete fidelity. The satisfactory utilization of the whole audio range in these processes depends on providing a chain of low-distortion equipment starting with the recording microphone and extending through the recording and reproducing equipment to the loudspeaker. Where any part of this chain introduces distortion, the use of extended-range reproducing equipment often produces sounds less pleasing than can be obtained from the use of a more limited range. But where the whole chain maintains the lowest possible distortion level, the utilization of the full audio range is mandatory for the best approximation of the original performance.

While there has been significant progress in the development of the electronic and electroacoustical components, the greater portion of this 30-year span has been characterized by a dearth of wide-range program material for home reproduction. Economics rather than technology has restricted the frequency range of most network broadcasts. The reverse was more or less the case for phonograph recordings. Most home listeners in the past have preferred to restrict the high-frequency response of their playback equipment rather than endure the high surface noise and distortion which was particularly irritating in the upper registers.

In very recent years recording equipment and techniques have been developed sufficiently to permit mass production of phonograph records for home use with coverage of essentially the whole audio spectrum at very low distortion and surface noise levels. Reawakening interest in FM broadcasting in this, the video era, is due in some measure to the wealth of excellent program material available to broadcasters in the new recordings. The current availability of prerecorded magnetic tape for home as well as broadcast use adds another source of low-distortion program material.

For most listeners, the limiting factor has shifted once more to the playback equipment. The component development lagging most significantly has been the loudspeaker, particularly in reproduction of the upper registers of the audio range. The industry has had some success in extending the upper frequency response of single dynamic speakers. However, the use of a single speaker to cover the whole audio range brings with it a prevalent, though little discussed, type of distortion. This is a Doppler-type modulation whose value is dependent on the frequencies being reproduced.

Better results are obtained when multiple speakers are used, each optimized for a particular portion of the range. Horn-loaded tweeters are capable of good high-frequency performance, but satisfactory units of this type are often somewhat expensive. Less expensive substitutes in the form of small dynamic cone tweeters have been used. The cone tweeter does represent some advance over larger conventional dynamic loudspeakers as far as the relative efficiency in radiation of high-frequency acoustic power is concerned, since the mass of the moving system is somewhat lower. Nonetheless, it is still substantial, being about 2 or 3 grams. At the higher audio frequencies, it becomes increasingly difficult to move the vibrating system at the desired velocities.

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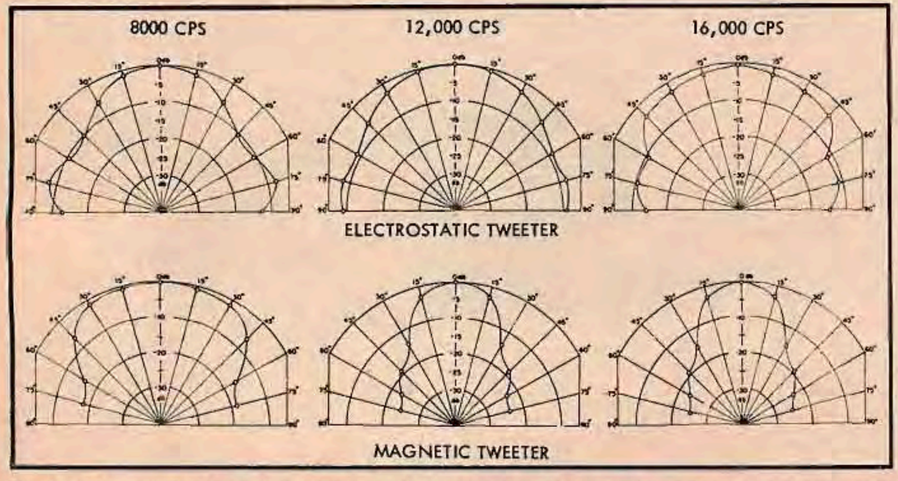

Fig. 2. Polar graphs show the directivity of the electrostatic tweeter contrasted with that of a conventional horn-loaded dynamic tweeter at three frequencies within the range of both.

The Electrostatic Speaker

Very recently another type of high-frequency loudspeaker has appeared in commercial production both in this country and abroad. This is the electrostatic loudspeaker, long recognized as a unit capable of excellent transient characteristics because of the very small moving mass and the distributed driving force. However, over 25 years of investigation had failed to develop an electrostatic speaker as a successful production item. Recently a form of the electrostatic speaker capable of mass production at a modest price was developed in the laboratories of Philco Corporation. This speaker has been incorporated in the new models of Philco's "high-fidelity" phonographs.

The failure of the electrostatic speaker to emerge as a commercial item in the past can probably be ascribed to two factors. Materials available for the diaphragm or membrane and the insulation have deteriorated too rapidly for incorporation in production equipment. Further, proponents of the electrostatic speaker have endeavored to cover the whole audio spectrum with a single unit.

The development of modern plastics has overcome the first handicap. Durable membrane materials, high in area-to-mass ratio, are now available. Plastics of desirable electrical insulation characteristics are on the market. The two desirable characteristics are combined in a new polyester membrane material.

The second handicap has been overcome with the realization that more effective results could be secured by multiple speaker units. Electrostatic loudspeakers operate most efficiently with closely spaced electrodes so that large excursions of the moving elements are not profitable. As a result, where attempts have been made to cover the lower audio registers, substantial areas have been used, areas measured in square feet. Such loudspeakers are exceedingly directive when reproducing higher frequencies. However, when the electrostatic loudspeaker is used in conjunction with a suitable dynamic loudspeaker which covers the lower and mid-ranges, the electrostatic speaker may be made quite small. By appropriate design, excellent polar distribution is possible.

The principles of operation of the electrostatic speaker have long been known. Professor Hunt's recent book contains an excellent discussion of the

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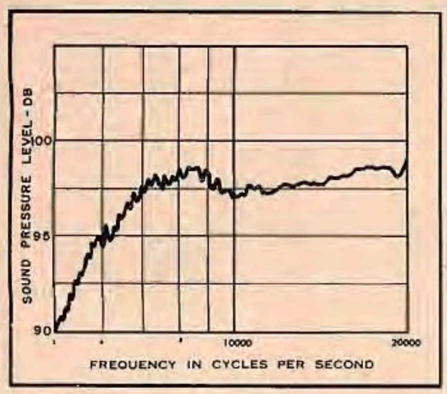


Fig. 4. Sound pressure response of the tweeter with a 30-volt signal and 300-volt d.c. bias.

subject.[1] Electrically, the electrostatic loudspeaker is essentially a capacitor, perhaps not a very good capacitor, since one of its electrodes may vibrate within certain constraints in response to the applied signal. This introduces a resistive component permitting work to be performed, in this instance, the production of acoustic power. Physically the unit consists of a fixed electrode, commonly called the backplate, and the vibrating electrode known as the membrane or diaphragm.

Both electrodes must be conductive, of course, so that if the vibrating element is an insulating plastic, it must be rendered conductive by the application of conductive material. The backplate must approach acoustic transparency at the lowest frequencies to be reproduced, in order not to increase the stiffness of the system in the operating range.

Since the electrodes are close spaced and the membrane has a high compliance, constraints are usually provided to insure separation of the electrodes. These constraints may be in the form of small spacer pips or strips, or they may be compressible material. Additionally, the membrane is usually held under tension in such a manner as to keep it separated from the backplate and to provide a restoring force opposing displacement due to electrostatic forces.

The vibrating system is set in motion by the electrostatic forces existing between the two charged electrodes in accordance with Coulomb's Law. The charge existing on the electrodes arises from two sources: a steady charge due to a polarizing potential and, superimposed on this, a varying charge which is the signal. The steady charge serves to increase the efficiency and to minimize the generation of distortion. The acoustic output is a product function involving both the steady and varying potentials.

The use of distributed electrostatic forces eliminates certain factors which give rise to distortion generation in loudspeakers driven by electromagnetic forces. Cone breakup in a dynamic speaker arises when the cone is driven by the voice coil at a frequency near one of the many natural resonances of the vibrating system because the cone is set in motion by the application of forces applied only in the region of the apex of the cone. Corrington has given an excellent treatment of this phenomenon.[2] Analogous behavior cannot occur in the electrostatic speaker because the vibrating system is set in motion by the application of electrostatic forces which are equally distributed over the whole area of the vibrating system. It, therefore, moves everywhere in phase, and no subsidiary modes are possible.

The use of modern plastic materials, conductively coated, for the diaphragm or membrane provides a moving element whose mass is small. Negligible energy is stored in the moving system. Air damping is adequate to stop the motion rapidly when the driving signal has ceased. The transient behavior of the electrostatic speaker is excellent. Oscillographs of the acoustic output in response to short bursts of signal disclose that the electrostatic speaker has superior transient characteristics when compared to expensive horn-loaded high-frequency loudspeakers. Cone-type tweeters are a poor third.

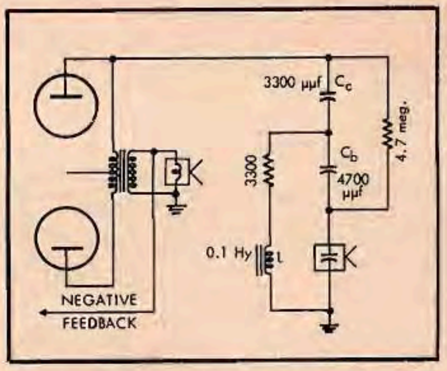


Fig. 5. Electrical circuitry shows method of connecting the speakers to the output stage.

Construction

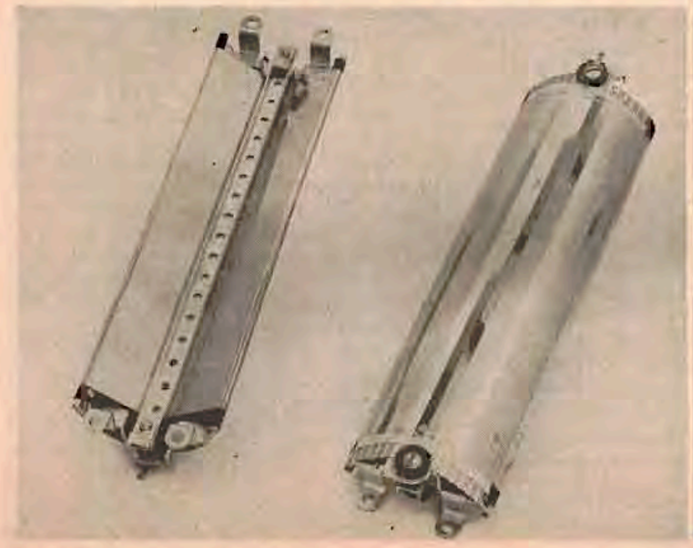
The electrostatic loudspeaker shown in *Fig.* 1 has several novel design features. One of the most significant is the semicylindrical form which accounts for its desirable field pattern. The speaker is mounted with the axis of the cylinder vertical. Acoustic energy is radiated quite uniformly in the horizontal plane but somewhat restricted in the vertical, corresponding to the requirements of ordinary home music systems.

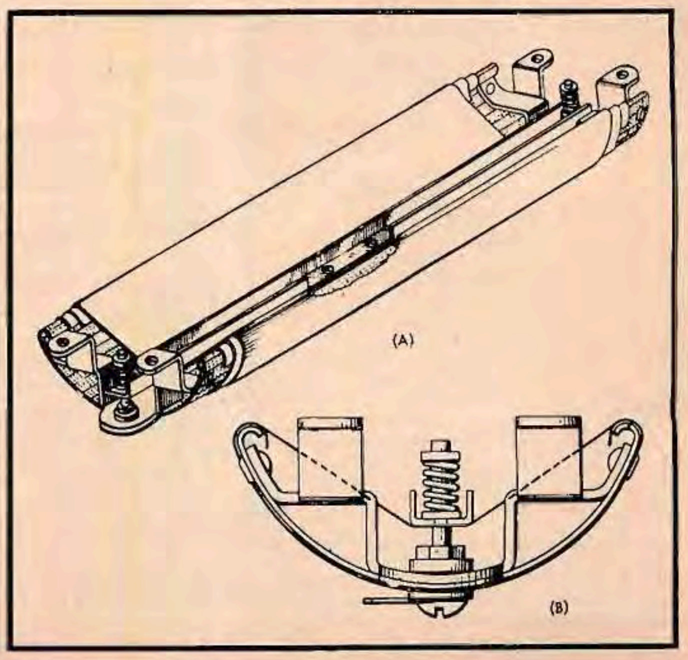
Close examination of *Fig.* 1 will reveal that rather than being truly a semicylindrical surface, the speaker is actually formed of sixteen slender facets. This assembly approaches a true cylindrical section since the width dimension of each facet is small compared to the wavelength of the highest frequency of the audio range. Effectively, a cylindrical wave is generated. *Figure* 2 shows polar curves of the sound-pressure response

[1] Hunt, "Electro Acoustics," John Wiley and Son, 1954.

[2] M. S. Corrington, "Transient testing of loudspeakers," AUDIO ENGINEERING, Aug. 1950.

Fig. 1, (left.) Front and rear views of the new tweeter. Fig. 3, (right.) These cutaway views show how the vibrating element, formed as a sleeve, is placed over the semicylindrical backplate and brought to tension by spring loading.





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at several frequencies. Polar distribution of a magnetic horn tweeter is also shown for comparison.

The stationary electrode is perforated aluminum on which vertical ribs are formed. These ribs act as the spacers to provide separation between the fixed and vibrating electrodes. The active area of the loudspeaker is that of the narrow rectangles lying between these ribs. Mounting feet attached to the backplate serve also to stiffen the assembly.

The vibrating element is fabricated as a sleeve of conductively coated plastic material. This unique design overcomes the assembly problem of stretching the membrane uniformly over a rectangular or circular frame. The sleeve is placed over the semicylindrical backplate and brought to proper tension by the application of a spring-loaded pressure plate as shown in *Fig.* 3. This eliminates variations in tension that may result from a slightly uneven mounting surface and also protects against changes in the speaker's characteristics should there be same small cold flow of the plastic membrane material.

This membrane is a film of a new polyester plastic .0005 inch in thickness. It is rendered conductive by a vacuum depositing process which places an exceedingly thin layer of metal over one surface. The plastic is characterized by high mechanical stability as well as dielectric strength. These properties assure minimum mass of the moving element consistent with mechanical and electrical requirements. The total mass of the vibrating system is about 1/10 that of cone-type dynamic high-frequency loudspeakers and is sufficiently small that it has little effect at the highest frequency of interest. The mass reactance of the vibrating system is comparable to the radiation resistance at the upper end of the audio spectrum. *Figure* 4 shows the frequency response of the electrostatic speaker. It will be noted that there is no h.f. fall-off in the audio range.

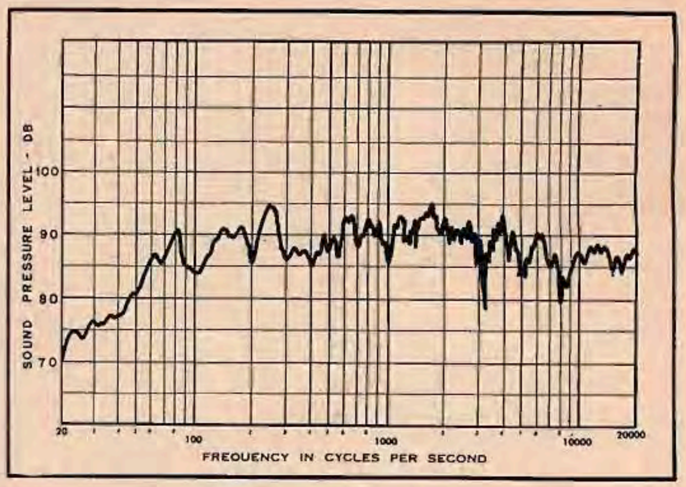

Fig. 8. Sound-pressure response of the phonograph of Fig. 7.

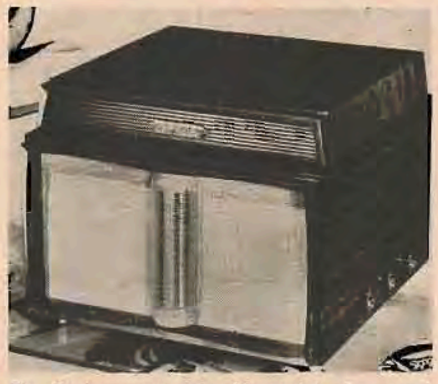

Fig. 7. A commercial table-model phonograph which includes the electrostatic tweeter.

Fig. 6. Impedance looking into the electrostatic tweeter coupling network is shown in (A). In (B) curve shows signal voltage across speaker.

Employment

In application, the electrostatic loudspeaker is used in conjunction with a companion dynamic loudspeaker, the two units being driven by a conventional push-pull audio amplifier. The crossover frequency is about 7,000 cps. This frequency was chosen because there are available many types of curved-cone dynamic speakers which exhibit reasonable efficiency up to about 7,000 cps. Above this there is a natural fall-off in acoustic power developed so that no electrical cutoff network is required for the dynamic speaker. It should be noted that although some dynamic speakers will exhibit good axial response above the 7-kc figure, the total radiated power, as measured by integrating the sound field, falls rapidly above this frequency. The impedance of the dynamic loudspeaker in the upper registers is largely inductive and its magnitude rises with frequency. In the region of the crossover and above, it may be many times the optimum load for the amplifier.[3]

The equivalent circuit for the electrostatic loudspeaker is given by Hunt.[1] For the design of coupling networks, however, only the impedance presented by the static capacitance between the two electrodes need be considered. In the model described, this is about 3000 μμf.

The coupling circuit is shown in *Fig.* 5. The network alleviates capacitive loading effects of the speaker and at the same time prevents the electrostatic speaker and its network from loading the amplifier in the operating range of the dynamic speaker. The Q's of both the series and parallel resonances are kept to appropriately low values by the 33,000-ohm resistor. No deleterious effects from the connection to a single plate of the push-pull output stage have been noted. The polarizing potential is taken from either B+ or the plate terminal. C_B is required for blocking.

The impedance seen looking into the coupling network of the electrostatic speaker is shown in *Fig.* 6 (A). The minimum of the curve is due to the series resonance of the coupling capacitor and the inductance. The maximum is due to the parallel resonance of the inductance and the series combination of the speaker capacitance and that of the blocking capacitance. It will be noted that the network is effectively removed from the amplifier throughout the operating range of the dynamic speaker.

The signal voltage developed across the speaker is shown in *Fig.* 6 (B). The variation across the useful range is about 2 db.

Figure 7 shows a typical application in a mass-produced table-model phonograph. The electrostatic high-frequency unit is protected by a perforated plastic housing which does not appreciably disturb the polar distribution. The axial sound pressure curve with constant input signal is shown in *Fig.* 8. This curve was taken with the tone controls set for flat response. There is, however, some low-frequency compensation, accomplished by a tap on the volume control, to offset the low-frequency loss due to the small size of the enclosure.

[3] F. Langford-Smith, "Radiotron Designer's Handbook, 4th ed., 1952, p. 837.

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