High-quality Electrostatic Headphones

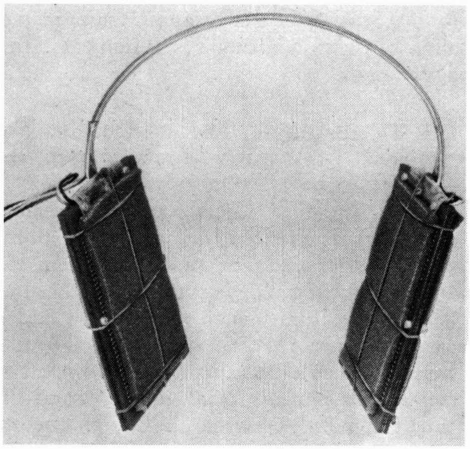
Theoretical and constructional details for simple electrostatic units producing plane wavefronts, and operating from the push-pull anodes of a valve amplifier

*by J. P. Wilson**, B.Sc., Ph.D.

The ability to hear sources of sound at their appropriate positions in space depends on several factors. The more familiar of these are the binaural cues; the nearer ear receives its message slightly earlier and, particularly at high frequencies, louder (Fig. 1). Other factors must also be involved because with binaural headphone listening all sounds appear to be within the head on a line between the two ears.

Two possible reasons for hearing sound sources out in space under normal conditions are motion parallax (the changes in the signals at the ears brought about by head and body movements) and the acoustic diffracting properties of the external ear. It was this latter factor which led the author to consider the present design.

The sound wavefront arriving from a source situated at some distance is nearly plane. It should be possible to stimulate this natural condition by providing a large flat radiator in which the signal is in phase all over its surface: in addition the radiator should be a poor acoustic reflector so that it does not re-reflect sound returning from the head and ears, nor form a semi-enclosed resonant cavity with the ear. An electrostatic device has characteristics which can approximate to these requirements.



The finished units with headband.

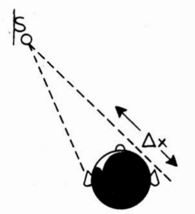


Fig. 1. The left ear hears information from S before the right ear.

Theory of electrostatic transducers

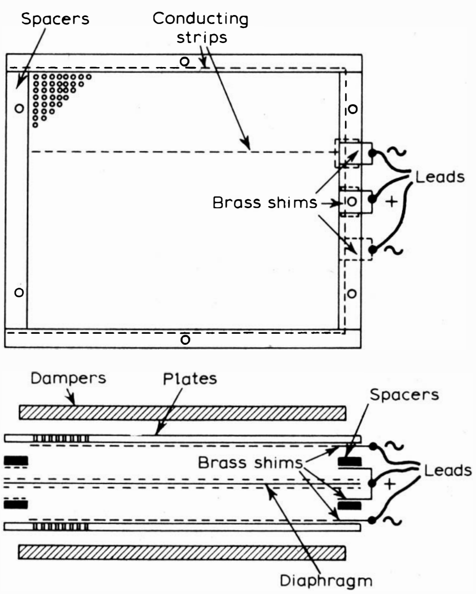
Hunt[1] has shown that for linear operation an electrostatic device should be push-pull, and operate with a constant charge on its diaphragm. If, however, parts of the diaphragm can move independently, the constant charge principle will not hold on a local scale unless the parts are electrically independent. This can be achieved by using a very high resistance coating.[2] The pressure at all points on the diaphragm will then be equal to the product of the field strength between the plates (produced by the signal voltage) multiplied by the charge density (derived from the bias voltage).

The motion of the diaphragm is controlled by the acoustic resistance of air at mid frequencies, by the mass per unit area at high frequencies, and by the tension of the diaphragm at low frequencies.[2] The high frequency roll-off is well above the audible limit for diaphragm materials commonly used in electrostatic speakers. At certain low frequency the entrained mass of air and the tension of the diaphragm form a resonant system.[1] This resonance determines the lower frequency limit of the device. It should not be made lower than required because this would limit the apparent sensitivity.[2]

The limitation on peak output imposed by the breakdown of air can be overcome by coating the plates with insulation.[1] At low frequencies, however, the limit will be set by the diaphragm touching the plates.

Other features considered by Hunt[1] to be desirable in an electrostatic speaker are concerned with altering the polar response and matching the impedance and are not applicable to a headphone design so will not be considered here.

Fig. 2. Constructional details of the units.



A practical headphone design

The practical starting point was an unpublished loudspeaker design by M. K. Taylor which gave many of the constructional details used here. It is proposed to deal with each of the elements in turn in such a way that the reader can modify design according to his own requirements.

The plates

These must be electrically conducting, acoustically transparent, non-resonant, rigid and flat. The first design (7in × 5in) used perforated zinc which has excellent acoustic properties (55% hole area) but is not sufficiently rigid for practical purposes.

Experiments with various hole patterns in hardboard revealed that the holes should constitute at least 20% of the total area and that they should be spaced much closer than the shortest wavelength to be reproduced in order to avoid internal resonance and presumably also diffraction grating effects.

The dimensions of the plates are determined by two considerations. They should be large enough to overlap the ears all round and must be of the appropriate size to give the desired bass resonant frequency to the diaphragm. The present unit used perforated paxolin boards (Lektrokit: Chassis Plate

*Dr. Wilson is involved in psycho-acoustic experiments in the Department of Communication at Keele University. His work concerns the spatial localization of sounds, and spectral and temporal aspects of auditory signal analysis.

No. 4:4¾ in × 4in) which provide insulation from the high voltages involved. These are rendered electrically conducting on their smoother sides as follows:

A stripe of high conductivity paint (Acheson Colloids Ltd.) is applied across the plate and brought out to a land for connection to the signal source (Fig. 2). The whole of the perforated area is then given a thick coating of colloidal graphite (Aquadag). In both cases care must be taken not to let any liquid run into the holes.

It is possible to dispense with the high conductivity paint (which is quite expensive) and make direct contact between the brass shims and graphite (Aquadag) lands on the plates.

When dry, the surface is polished with a dry cloth to remove any surface irregularities, or hairs, and blown thoroughly clean. A flame can be applied quickly to the surface just before assembly to remove any remaining dust or lint.

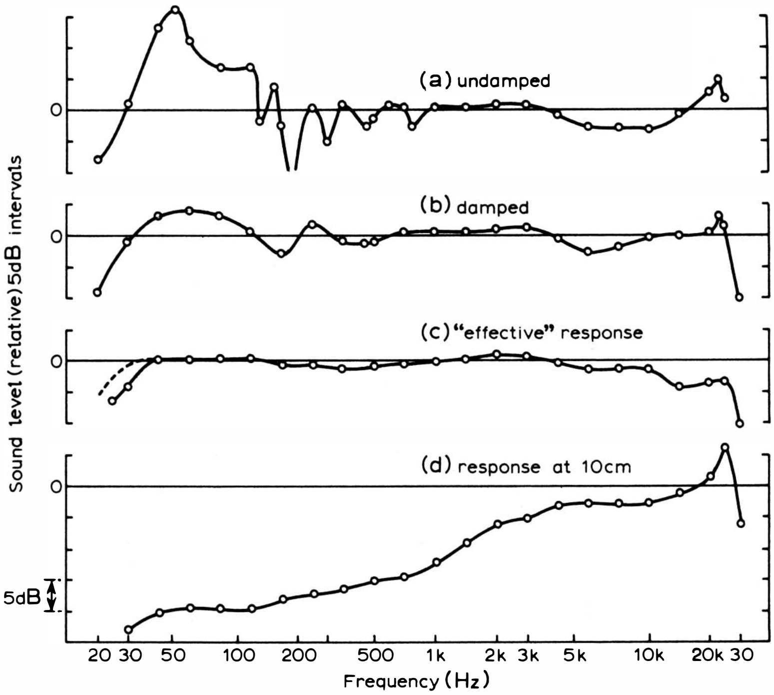


Fig. 3. Graph of frequency response against relative sound levels.

The spacers

These must have excellent insulating properties and be uniform in thickness. The actual thickness is not critical: thicker spacers will allow larger excursions at low frequencies but will require correspondingly greater signal and bias voltages to produce a given sound pressure.

Acetate sheeting of 0.04in. thickness was used for the spacers and stuck to the plates with Evostick. This thickness was chosen partly to ensure uniform response in spite of small deviations from flatness in the plates and might with advantage be reduced to about 0.025in. in less critical applications particularly if less bias and signal voltage is available. The holes required around the edges can be drilled after the spacers are fixed (Fig. 2).

A stripe of high conductivity paint (or Aquadag) is applied near the inner edge of the spacers for connection to the bias supply.

The diaphragm

This consists of a thin resistively coated film of stressed plastic of the type used by supermarkets for wrapping foodstuffs (Goodyear: Vitafilm). It is soft and acoustically dead, readily heat stressed, and is available in 0.0005in. and 0.001in. thicknesses.

The thinner material was chosen because it would be damped more readily by the acoustic loading.

The resonant frequency of the diaphragm will depend on size and shape, mass and tension. Too low a resonant frequency is undesirable because this will also necessitate using a lower bias voltage consequently lowering the sensitivity. It would also render the device more sensitive to any unwanted subsonic signal. The paxolin version has a resonant frequency of about 50Hz in free space which when damped leads to a −3dB point of about 30Hz.

In practice the proximity of the ear and head reduces these frequencies by about half an octave presumably by increasing the effective mass of entrained air.

A conductive coating is needed on the diaphragm to allow it to charge up to the bias potential and to counteract any leakage of charge. But it should not be so conductive that charge can flow around during signal movements or linearity will be lost. A resistance within the range 100-10,000MΩ measured between two parallel electrodes 1in. long and separated by 1in. would be satisfactory (a just detectable deflection on a 50μA meter when fed from 250V).

To prepare this coating the plastic sheet is pressed on to a piece of moistened glass using a rubber roller. When the upper surface is dry a little colloidal graphite is rubbed on with cotton wool. At first it wets the surface in a thick black layer which by further rubbing, using the same piece of cotton wool, is nearly all removed leaving a shiny surface just noticeably darkened.

When the whole surface is within the required resistance range it can be turned over and coated on the other side. (The water will not harm the first coating unless it is rubbed hard.)

The finished diaphragm can then be stuck with Evostick to the spacers on one of the plates and pressed between two flat surfaces to dry. Only the minimum of adhesive must be used so that it does not spread between the diaphragm and the conducting stripes.

Heat tensioning may be performed in several ways. The method of Taylor was to use a fan heater with restricted air flow: the method adopted here was to place the diaphragm assembly under a hot grill for a few seconds. The plastic goes soft and then the wrinkles shrink out: it can then be removed and the tension builds up further as it cools. The process may be repeated if for any reason it appears necessary.

The resonant frequency and therefore the tension appears to be constant for a given size of diaphragm. This ability to obtain a controlled tension is probably the chief advantage this material has over other plastics.

The two halves are next bolted together with 6 BA nylon nuts and bolts. Thin brass shims should be inserted in the appropriate positions to make contact with the conducting stripes.

A single shim may be used for the bias supply if a small nick is made in the edge of the diaphragm allowing contact with the conducting stripes on both sides. Leads may then be soldered onto the shims and well insulated.

It is probably better to bind the three separate leads together at a few points only rather than twist them or use three-core cable, otherwise the capacitive load on the amplifier may be too great.

Acoustic damping

Without extra damping the response below 1kHz is really quite irregular, as shown in Fig. 3. The plates themselves contribute a certain amount of damping as was deduced by comparing a similar diaphragm made on an open frame which had very characteristic drum-like properties.

Whilst it may be possible to obtain the desired damping by using plates with a very large number of minute holes this alternative was not pursued as the method adopted is simple and satisfactory, and in addition produces further electrical insulation. This consists of sandwiching the units between 4mm layers of foam plastic attached with rubber bands, or sewing together the edges of the foam layers to form an envelope. Adhesive was not used because of the danger of filling the perforations and because it was thought desirable to be able to inspect the diaphragm from time to time.

The effectiveness of this treatment can be judged by comparing (a) and (b) in Fig. 3. Doubling the thickness does not lead to any further improvement.

Finally a headband is arranged to hold the units flat against the ears and just in contact. This can be a 12in. × ½in. strip of 16 gauge Duralumin bent to shape and given a slight twist at each end to hold the units flat against the ears. Owing to their light weight, lack of pressure and good ventilation these

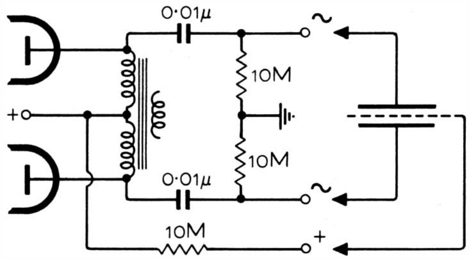


Fig. 4. The electrical circuit for connecting the phones to a push-pull output valve amplifier.

headphones can be worn indefinitely in complete comfort.

Electrical considerations and maximum output

As the impedance of an electrostatic device is predominantly capacitive it presents its lowest impedance at maximum frequency. For optimum performan

dance should be sufficiently low to cater for the highest frequency. Below this the output will be constant and limited by the maximum output voltage of the amplifier down to the lowest frequencies where plate spacing further limits the maximum output.

As the capacitance of the headphone unit is only about 80pF including leads it would be possible to utilise a step-up transformer between the anodes of a push-pull amplifier and the unit. However, the high inductance and low capacitance required to cover the whole audio frequency range in such a transformer would be difficult to achieve particularly in view of the high insulation required.

The output voltage available from push-pull anodes (Fig. 4) is adequate for most applications, however, and there would be little point in having much greater available output at medium and high frequencies than at low frequencies.

Besides its simplicity this method has the advantage that internal insulation of the plates is unnecessary unless the spacers are reduced to below 0.025in because the breakdown of air is not reached. A high quality output transformer may be used to step up the output of a transistor amplifier to a comparable voltage but separate provision would be needed for biasing.

Insulation of the plates would be necessary only for very high outputs and it would be practicable to obtain this only over a restricted frequency range.

After preliminary insulation tests to check construction the bias voltage should be applied. By observing the shape of objects such as a window opening or a fluorescent tube by reflection from the diaphragm it is possible to see that it is flat and not plastered against one of the plates.

The bias voltage should be set so that even when the diaphragm is blown towards the plates it will return to the central position by its own tension.

Using a Radford STA 15 (a 15W amplifier with h.t. supply at 375 volts) with no resistive load, the free field r.m.s. sound pressure is limited to 90dB (rel. 0.0002 dynes/cm^2) from 30Hz upwards by the voltage handling capacity of the amplifier. (As some amplifiers become unstable without a resistive load it would be safer to include this and accept the reduced output if stability cannot be checked by the user.) By reducing the spacers to 0.025in the output above 60Hz is increased to nearly 100dB before the amplifier overloads but below 35Hz the maximum output would be limited to less than 90dB by the diaphragm excursion.

The actual sound pressure at the ears is about 10dB greater than the free field pressure due to the reflective and sound gathering properties of the ear and head. This would also apply to loudspeakers, and indeed natural sounds, but not to headphones. The exact magnitude of pressure increase is dependent on frequency and on the direction of the source in space relative to the ear.

Performance tests

The units were tested for frequency response and square wave response using a B & K 4133 microphone in contact with one of the plastic dampers.

This was done in several positions as uniformity cannot be assumed for the following reasons: uneven spacing between the plates causes variations in the signal field strength; tension controlled motion at low frequencies gives a curved deflection profile (with highest sound pressure in the centre) whereas air resistance controlled motion at high frequencies gives a constant displacement (apart from the extreme edges) and a uniform sound pressure; nodes and antinodes may be formed; a leakage path causes reduced sensitivity in this region.

Fig. 3 shows the frequency response under a number of different conditions: (a) shows the performance just off centre without the plastic dampers. There is a resonance at 50Hz and a number of peaks and dips up to 1kHz.

Curves taken in other positions (not illustrated) had the same main resonance but the frequencies of intermediate peaks and dips were quite variable. It is assumed that these were due to the formation of nodes.

Curve (b) taken at the same position illustrates that the effect of the foam plastic was to damp out all these irregularities. Curve (c) is an averaged response over an area of the diaphragm corresponding to the size of the ear.

Taking into account the lowering of resonance when in proximity to the ear (dashed line) the effective bandwidth is 25Hz – 25kHz ± 3dB without any sharp peaks or dips (all maxima and minima are plotted).

One of the interesting features of a device like this is the polar response pattern. If λ is the wavelength of sound, r, the radius of the generating surface, and x, the perpendicular distance from the centre, then for very low frequencies when $\lambda >> r$, the response pattern is a figure of eight.

Initially when $x << r$ pressure falls off slowly with distance but as x increases and becomes much larger than r, the response tends towards an inverse square law.

For very high frequencies, however, when $\lambda << r$, the device acts as a plane wavefront generator. Sound pressure is uniform across the beam (projected area of the diaphragm) and independent of distance but falls off rapidly outside the beam.

In practice, of course, much of the sound spectrum lies in the intermediate region ($\lambda \sim r$) and the characteristics will lie between the limiting cases outlined above.

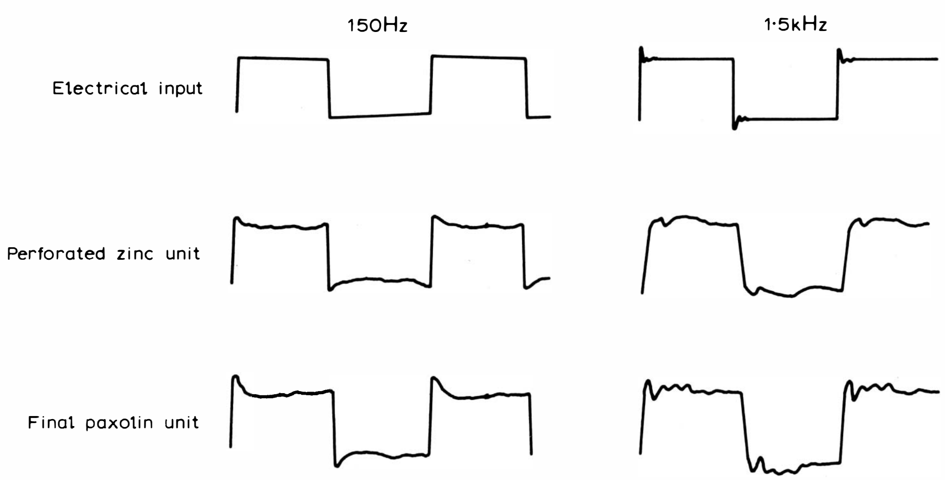
It is obvious from these considerations that this does not form a suitable basis for a loudspeaker as the frequency response would vary greatly with distance and off-axis angle. This variation is reduced in full range electrostatic speakers by dividing up the frequency range and feeding the components into separate sections.

To illustrate the above points the frequency response has been plotted at 10cm from the diaphragm in Fig. 3(d).

In headphones the condition that $x << r$ is easily satisfied and the wavefront should be nearly plane at all frequencies so that small changes of position or distance make little difference to the sound pressure. For reproducibility of psychoacoustic thresholds this represents a distinct advantage over conventional phones.

The square wave response is shown in Fig. 5 for the same microphone placement as Fig. 3 at 150Hz and 1.5kHz. This shows the

Fig. 5. Square wave response at 150Hz and 1.5kHz for the two types of unit mentioned in the text.



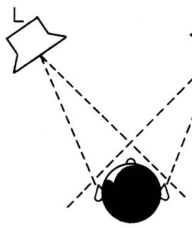


Fig. 6. (left). The effect of crossed soundpaths. Fig. 7 (right). Units put in parallel to simulate crossed soundpaths.

excellent phase characteristics of the units. The "ring" at 25kHz indicates the internal resonance referred to above and is also apparent in the frequency response curves. Obviously at this frequency, so far outside the audible range, it is of no consequence.

Harmonic distortion was measured at a number of frequencies at a sound power level of 80dB. The second harmonic ranged from about 0.5% at low frequencies (50 – 200Hz) down to about 0.2% at higher frequencies. Third and higher harmonics were less than 0.1% at all frequencies.

Different methods of assessing the transmissive and reflective properties of the units did not lead to consistent results. The reflection coefficient may be about 0.1 up to 1kHz rising to about 0.5 at 6kHz and perhaps falling above this.

With a probe microphone situated at the entrance to the ear canal it appears that the difference in response between using the electrostatic earphone and a source of sound at some distance, in a comparable direction, can be represented by a series of peaks and dips of 2—3dB in the region of 2kHz upwards. Although these are less than the fluctuations in response produced by the external ear itself (which in turn are dependent upon the direction from which the sound arrives) it should not necessarily be assumed that they can be neglected.

The author wearing the headphones.

Subjective impressions

Several types of signals have been demonstrated to a number of observers including "hi-fi" enthusiasts, but not professional listeners. All were most favourably impressed by the smoothness and lack of coloration of white noise, the dead sound of clicks, and the naturalness and sense of presence of stereophonic music. They were unanimous in preferring this to any system of reproduction heard previously.

Distortion and other shortcomings in the signal source are of course also heard with greater clarity. Part of the increase in clarity is no doubt due to the absence of room reverberations.

Spatial effects

As the intention of the design was to simulate sound sources at a distance, the spatial effects are of particular interest. Although these effects cannot really be called natural they are far from disappointing.

Sounds appeared to be coming from many different distances as well as many directions, including, surprisingly, some above and below the horizon. Regrettably, however, a few sounds still persisted within the head or in close proximity to the ears. It was thought possible that part of this exaggerated impression could be due to the absence of the crossed soundpaths shown in Fig. 6.

A simulation of these was made by introducing two further units *R'* and *L'* connected in parallel with *R* and *L* respectively (Fig. 7). This did not effect any improvement, and it must be noted that these "crossed" paths would be deficient in low frequency components because of the distance of the units from the ears—see Fig. 4(d).

Furthermore, it must also be noted that the wavefront produced by a unit represents a single direction of sound only and will be inappropriate for other directions.

This limitation is shared by loudspeaker stereophony in which the illusion of sounds arriving from between the loudspeakers can be dispelled by rotating the head.

The great improvement in the externalization and spatial representation of sounds compared with conventional headphones, however, indicates that it is better to have directional information which is sometimes inappropriate than none at all.

Further experiments using the larger perforated zinc units fixed in space to allow small head movements were also disappointing. It does not appear that motion parallax alone is the final requirement for realism.

Conclusions

The units described obviate some of the difficulties inherent in normal headphones for psychoacoustic work: variations of sound pressure with position on the ears and with efficiency of seal; poor response at low and high frequencies; and poor phase response.

On the debit side electrostatic headphones provide no sound isolation, and methods of overcoming this limitation tend to degrade the performance.

For music reproduction they provide greater fidelity than either conventional headphones or loudspeaker systems. They share with conventional headphones the absence of room reverberations but surpass them for spatial realism. They fall short of loudspeakers in providing spatial realism but provide greater clarity and separation.

Thanks are due to Mr. J. R. Ruscoe for constructing the units.

REFERENCES

1. Hunt, F. V., *Electroacoustics*, Harvard University Press, 1954.
2. Walker, P. J., Wide range electrostatic loudspeakers, *Wireless World*, May, June and August, 1955.

Our Next Issue

Speech Recognition. Part 1 of a two-part article on the automatic recognition of spoken English will investigate the elements of speech that can be differentiated most simply by a machine. These are called phonemes, and are not identical with syllables.

Digital Exposure Timer. A timer designed by a photographer for photographers, and built on digital elements, will be described with full details–theoretical and practical. The design meets the timing accuracy and range required in colour photography, whilst the components are cheap and readily available.

Circuit Ideas. We will be starting a new regular feature—selections of original circuit ideas submitted by readers. These circuits were sent to us in response to the open invitation headed "Circuit Ideas" which appeared in the June and July issues of *Wireless World*. The request was (and still is) for functional 'bricks' which have proved useful to somebody at some time. Performance, originality of realization and economy of components are the most important criteria in selection. Five guineas will be paid for each circuit published.