Electrostatic Headphone Design

Instructions for making a simple and inexpensive high-quality unit

by Philip D. Harvey, B.Sc.

The design described below, like that published in 1968[1], is based on the constant charge push-pull principle schematically illustrated in Fig. 1. The constant charge is derived by feeding the diaphragm from a high resistance *R*, and relying on the capacitance of the earphone to store the charge.

Basic requirements in construction are that:

1. the fixed plates be rigid, acoustically transparent, and both flat and conducting on the inner surface;
2. the spacers be flat, of uniform thickness and, above all, insulating; and that
3. the diaphragm be flexible and light.

In all, three models were constructed. In producing fixed plates for the final model the electro-mechanical analogy described in Appendix B was used.

Stroboscopic examination of an earphone had shown that the diaphragm behaves as an elliptical vibrating piston with major and minor axes set by the spacers. These dimensions were set at 75 × 45 mm to cover the ear. A short transmission "tunnel" is employed to improve low-frequency coupling with the ear. This extension is lined to reduce resonances.

The fixed plates are of single-sided copper-plated fibre-glass. Hole area is 30%—sufficient to ensure acoustical transparency without sacrificing rigidity. The holes must be deburred after drilling.

To remove the risk of charge leakage at the edges of the board and at the connecting bolt holes (due perhaps to tearing of the diaphragm and consequent shorting) about 2 mm of copper is removed from the edges of the board round the connecting bolt holes (see Figs 2 and 3) to prevent charge leakage should the diaphragm tear at the edges.

The spacers, made of polyvinyl acetate, are cut in one piece from a sheet to avoid poorly insulating joints. These are drilled, using the fixed plates as templates, and deburred.

To make a safe connection of high voltage leads, two methods can be employed for the outer plates:

(a) Alternate unrounded corners of each fixed plate are removed to allow a connection to be made to the other fixed plate. Plasticine can be used for insulating the connection. The principle is illustrated in Figs 4 and 5.

(b) A small hole may be drilled in one corner of the fixed plate, and the copper side of the board slightly countersunk. The insulation of the signal wire is then stripped off, the inner being tinned and fed through the hole, as shown in Fig. 6. The well, created by countersinking, is now filled with solder which makes good contact with both the wire and copper plating. By grinding this surface flat we have a good safe connection.

To insulate the diaphragm connection it was decided to utilize the insulating properties of both the fixed plates and the transmission tunnel. The connection was brought to the surface of one fixed plate by a brass bush as shown in Fig. 7. The connection was then made harmlessly between the tunnel and board.

The film for the diaphragm is prepared by taping it crease free over a wooden frame of inside dimensions 200 × 250 mm. The frame, with the film now flat and under tension on its upper surface, was placed over a sheet of glass 240 × 190 mm of slightly greater thickness than the frame. Under these conditions it was easier to rub Aquadag on and off the film. This should be continuous until surface resistivity is $10^8\,\Omega$. The prepared film is next mounted on one spacer using double-sided Sellotape with the resistive side exposed, and laid on to the other spacer and a fixed plate with the brass bush inserted. The brass bush

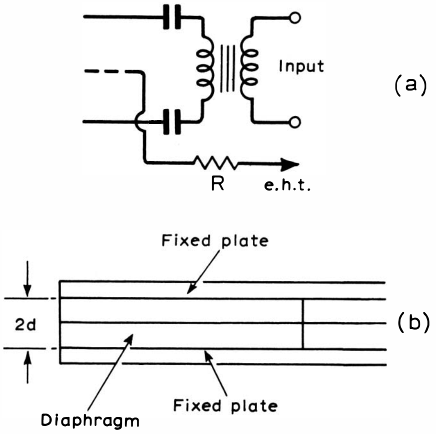

Fig. 1. Push-pull electrostatic sound generator.

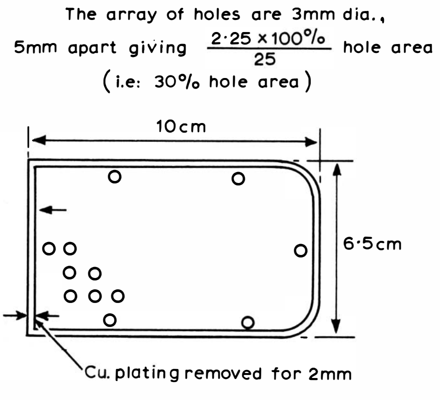

Fig. 2. Plan view of fixed plate.

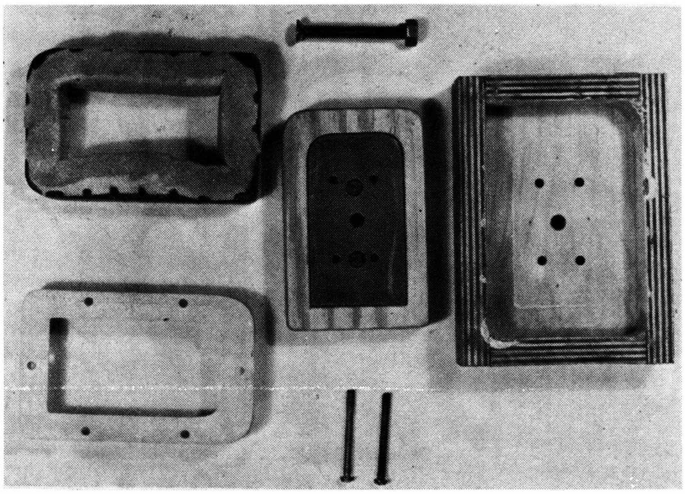

Fig. 3. Mould used for the transmission tunnel, and typical results achieved.

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[1] 'High-quality Electrostatic Headphones' by J. P. Wilson, *Wireless World*, Dec. 1968.

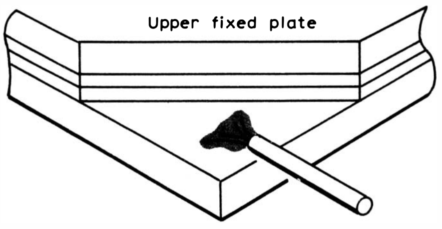

Fig. 4. One corner of final model.

now contacts the resistive coating, although it might be necessary to use some Aquadag on the contacting surfaces. The other fixed plate is laid on the assembly, followed by the transmission tunnel ready drilled, enabling the parts to be fastened together with nylon nuts and bolts. The components are shown in Fig. 5.

Before testing, the earphone is heated by warm air to tighten the diaphragm and remove any slight creases in it.

Transmission tunnel details

The transmission tunnel must be light and strong, and transmit the sound produced by the earphone to the ear. The simplest shape to do this is shown in Fig. 9. The only readily available group of materials to fulfil the above conditions is the plastics. These also have an advantage of damping incident sound, whereas metals tend to 'ring'.

The idea of casting the tunnel from polystyrene was investigated. Experiments led to the use of a wooden mould. It was found that if the mould was left overwaxed, then the excess wax was melted during the ensuing catalytic process, and this enabled the polystyrene to be removed from the mould whilst it was still pliable. Provided it was well supported whilst setting fully, the result was quite acceptable. Both the mould used (made of two parts for easier positive removal) and a typical positive are shown in Fig. 3.

Tunnels of both clear and coloured polystyrene were made, and it seems that the colouring material used gave the tunnel added strength.

It was found that latex foam rubber, used for lining the tunnel because of its excellent sound absorbing properties, was best cut on the bandsaw.

Variation of the other component elements

Under given conditions of signal and bias voltages, the two components affecting the earphone's performance are:

(a) The spacers—the thickness of which determine E and hence sound output. Spacer thicknesses of 0·18, 0·25, 0·37, 0·62 and 1 mm were tried. Decreasing the spacer thickness did not alter the frequency response but raised the sound level. Construction difficulties increased as spacer thickness decreased due to the slight and unavoidable warping of the fixed plates. This did not become too bad until ionization of the air was also a problem (see below).

Silicon resin bonded paper, paxolin, and dry paper were also tried as spacer materials. No difference was observed in the performance and it is concluded that any material having a resistivity greater than $10^{10}\,\Omega$ cm would be satisfactory.

(b) The diaphragm—through which no appreciable current should flow in less than half the time period of the lowest frequency to be reproduced. This ensures constant charge conditions. If one assumes the diaphragm to be perfectly conducting, and the earphones to have capacitance C farads, and further that the lower limit of audibility is 27 Hz, then the diaphragm must be fed via a resistance R ohms, such that;

$$RC > \frac{1}{2\times 27}\text{(approx.)}.$$

$$\text{C is calculated as 330 pF from } C = \frac{\epsilon A}{d}$$

$$\text{whence } R > \frac{1\times 10^{12}}{54\times 330}\text{ i.e. } R > 6\times 10^{7}\,\Omega.$$

Due to the high value of this resistance it is easier to make the diaphragm resistive than feed it through an external resistance. Experiments were made with sheets of $10^{7}\,\Omega$ surface resistivity and greater. As expected the bass response improves as the resistance increases. The high-frequency

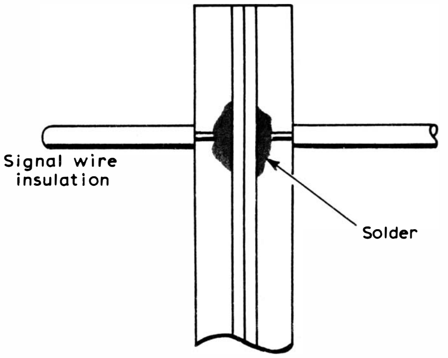

Fig. 6. Cross-section of alternative final model.

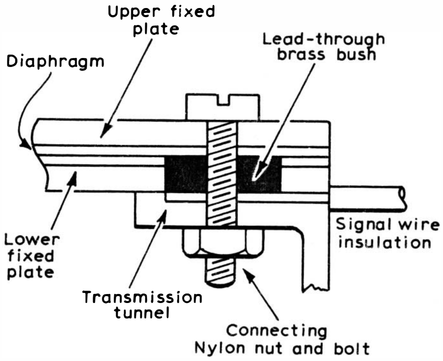

Fig. 7. Cross-section through connection to diaphragm.

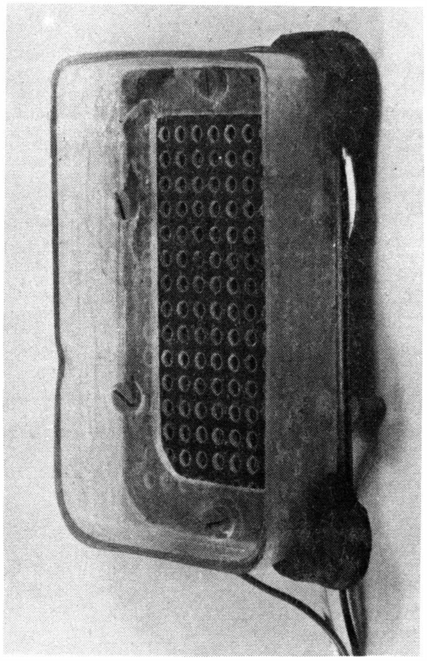

Fig. 8. The completed final earphone.

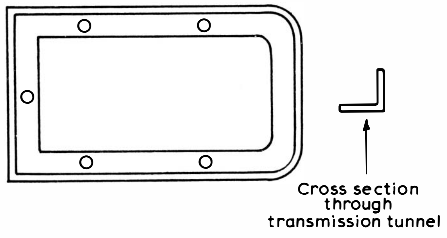

Fig. 9. Basic transmission-tunnel shape.

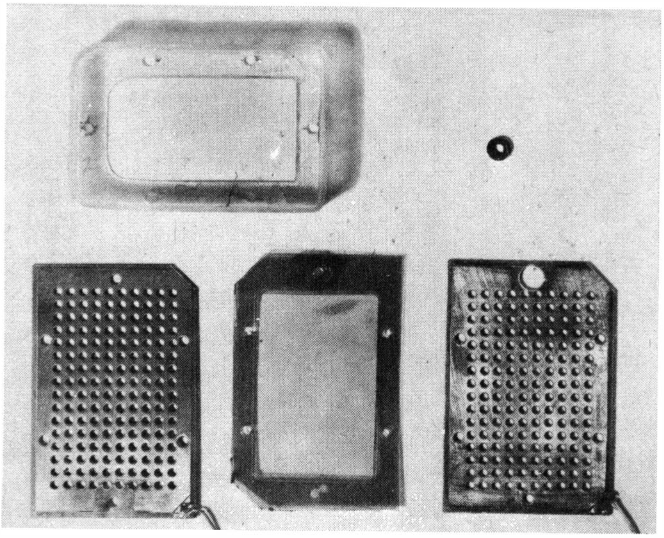

Fig. 5. Component parts of the final model.

response also improves, due presumably to the lower mass resulting from less graphite on the film. As some charging current must flow on to the diaphragm there is some limit to how high the resistance can be. Best results were obtained at the limit of measurability, i.e. a surface resistivity of approximately $10^9\ \Omega$.

Hospital anti-static polythene was tried and though it worked, the type available was thick and heavy, with a surface resistivity of only $10^5\ \Omega$. Hence both high and low frequencies suffered.

Various materials of the same type (Vitafilm) were obtained from local supermarkets. These were analysed spectroscopically and found to be the same material with the exception of that supplied by Sainsbury's. Microscopic analysis then showed that Vitafilm because of its porosity was not very suitable. The film made by The Borden Chemical Company was judged to be best closely followed by that made by Filmco in Durham.

Further tests to discover how best to apply homogenous resistive coating to the film were made on Borden's film. The use of evaporation techniques were first studied, but these posed three problems. In the conventional evaporator the film surface exposed was not large enough for an even film to be deposited over a sufficiently large area. Also at the low temperature required (not to destroy the film) oxidation of the depositing metal occurred. Finally when a film was deposited the metal permeated the plastic, altering its properties such that it became brittle and unusable.

Dry graphite powder rubbed into the surface did not alter its resistivity, presumably because the particles did not interlink and form molecule chains.

Finally a method was considered whereby a conducting medium could be sprayed as a solution in a liquid that would attack the film and hence give a permanently resistive surface. Graphite does not readily dissolve in any p.v.c. solvent, and so could not be used. A solution of silver in methyl acetate (Silver Dag) was sprayed on to a film, soaped to lower surface tension. The results were encouraging but a less active solvent would have to be used. Before pursuing this method, diluted Aquadag was substituted for Silver Dag and found to leave a completely uniform layer of graphite on the film when dry. Although this coating could be made fairly thick its resistivity remained immeasurably high until it was rubbed. Experience soon showed the amount that had to be sprayed for the required resistivity.

Drive circuits

Provisional model

The circuit shown in Fig. 10 employs the output stage of a commercial valve amplifier. The surface resistivity of the diaphragm must be greater than $10^8\ \Omega$ and hence the $10^7\ \Omega$ resistor in the feed line to the diaphragm is not necessary, but an added safety precaution.

It was found that the 0·01 μF isolating capacitors were sufficiently leaky to allow the outer plates to attain a high voltage, and the diaphragm could be earthed as an alternative form of bias. This makes the diaphragm an effective negative charge. This is not desirable because a steady high voltage on the outer conducting plates could be dangerous.

With the earphones in the circuit as shown, distortion was apparent, even at low acoustic levels. This was thought to be due to the output transformer. This amplifier was not designed to operate at maximum output continuously, and under these conditions inter-modulation distortion sets in. The earphones require a high voltage signal, but very little current. With this in mind an amplifier to deliver a distortion free signal was designed.

Designed valve amplifier

With a spacing of 0·37 mm (which changed by only 10% at full bass output) the maximum permissible voltage between the diaphragm and either fixed plate, to avoid ionization of the air between them, is 1000 V. With 300 V on the diaphragm this means that the maximum peak-to-peak voltage level on one plate can be 500 V. This leaves a large margin of safety for humid days or signal surges. The circuit of Fig. 11 was used giving only 400 V peak signal, as the valves and components were readily available. It gave no distortion observable on an oscilloscope, even without negative feedback, due presumably to the light loading on the amplifier.

Its use gave immediately discernible improvement in output level and fidelity.

Designed transistor amplifier

40 V rails are commonly available on transistor amplifiers and the circuit of Fig. 12 was built giving 32 V peak signal. Using 300 V rectified mains on the diaphragm gave a barely audible output.

The circuit of Fig. 13 was designed to give 300 V peak output. Any n-p-n silicon transistor with a $h_{fe}>50$ at 1 mA and a

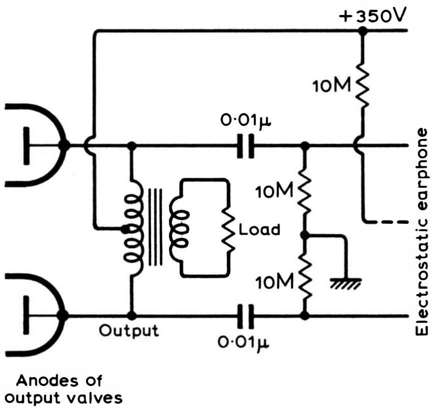

Fig. 10. Modified output of a commercial valve amplifier.

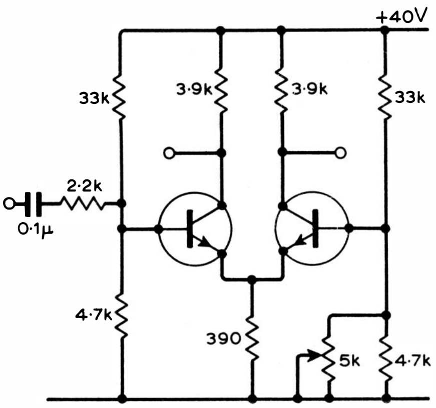

Fig. 12. Differential amplifier providing 32 V output.

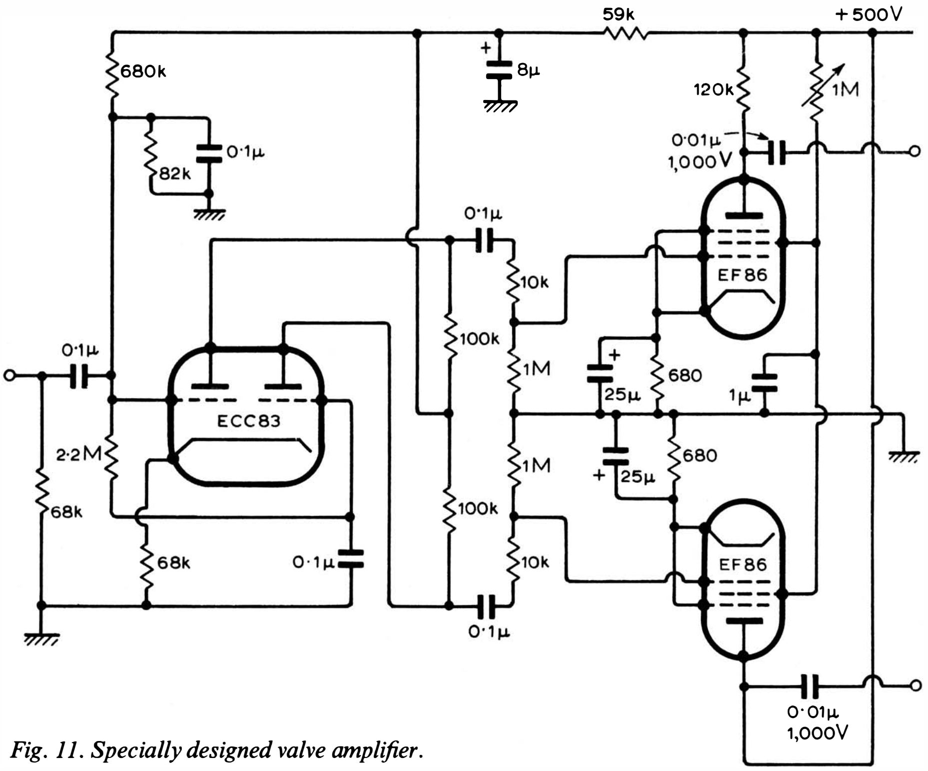

Fig. 11. Specially designed valve amplifier.

$V_{ce} > 35$ V will do for the first stage. The transistors in the differential stage should preferably be matched.

Three potentiometers are included to set up the amplifier to its optimum performance. First use R_1 to match the base voltages of Tr_1 and Tr_2; then adjust R_3 to make the average collector voltage of Tr_3 and Tr_4 115 V. Finally, using R_2, balance these collector voltages; repeat this procedure until both Tr_3 and Tr_4 collectors are at 155 V.

Measurement and analysis

From the section below and Appendix A the optimum of all the variables may be found. Although the thinner the spacers used the more the acoustic output obtained, it was found with the thinner ones (0·18 and 0·25 mm) that the air ionized on more humid days. This was apparent as a clicking noise, varying in repetition rate from one to ten hertz. It arose because constructionally the fixed plates are never equidistant from the diaphragm, and the air between the diaphragm and closest plate ionizes first. This allows attraction to the other plate increasing E, so that air here ionizes while the other reconstitutes itself. This effect is eliminated by reducing the voltage on the centre plate, but this necessarily reduces sensitivity.

The 0·37 mm spacers were therefore chosen and a plot of output versus central electrode potential revealed a levelling off at about 600 V. This is unexplained, but below this value the measured output is very near to the calculated value.

Many listeners were satisfied with volume and fidelity using 350 V on the diaphragm and the designed valve amplifier. There were many comments on the "depth" of the sound, which is due to the fact that plane waves are arriving at the ear, and these are normally associated with a distant source by the hearing mechanisms. When in use on a stereo system this effect makes it easier to identify the direction from which the sound appears to come.

Results achieved

Traces of the frequency responses are given with markings of 10 dB intervals and at the frequencies 20 Hz, 100 Hz, 200 Hz, 1 kHz, 2 kHz, 10 kHz and 20 kHz.

Fig. 14 gives the responses with different input signal voltages. The effect of increasing this voltage should be the same as decreasing spacer thickness. The relative graphs show this to be true, though the relative amplitudes differ.

Fig. 15 displays the difference made by altering the potential on the centre electrode.

Fig. 16 displays the difference in characteristic responses when plotted in the open air, and when plotted in the artificial ear.

Fig. 17 shows the best response achieved and corresponds to all the variables being optimised. The component specification for this is:

spacers—polyvinyl acetate 0·37 mm thick;

diaphragm—Borden Chemical's plasti-

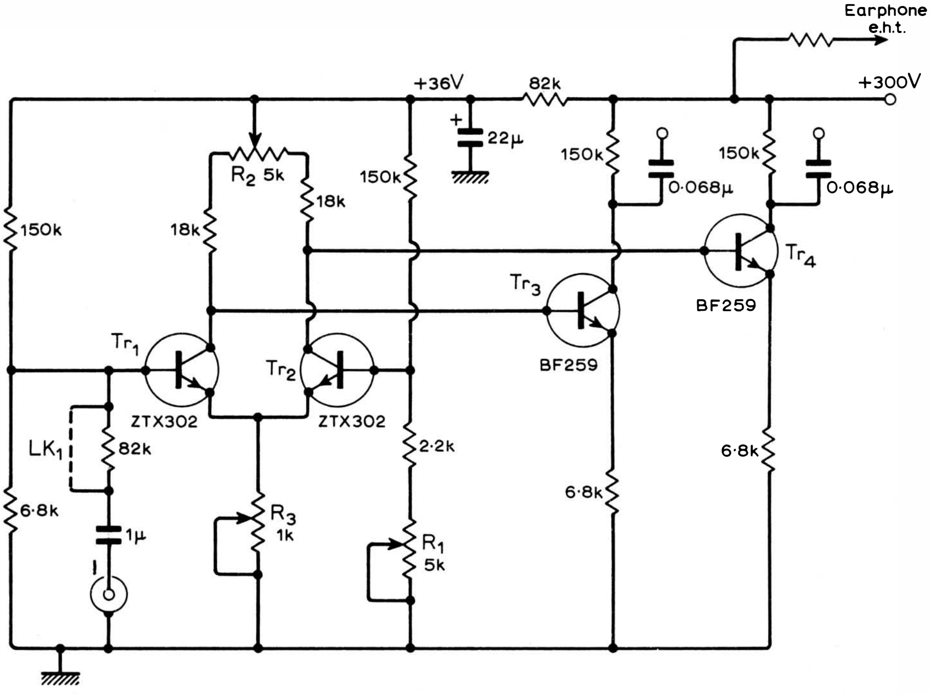

Fig. 13. Suitable transistor drive amplifier providing 300 V peak output.

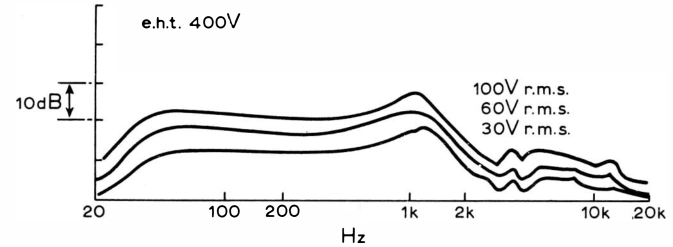

Fig. 14. Response for different signal-voltage levels.

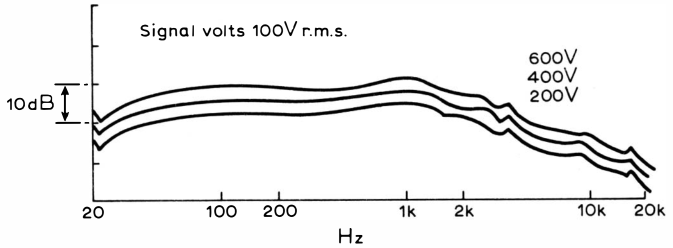

Fig. 15. Response for different diaphragm voltages.

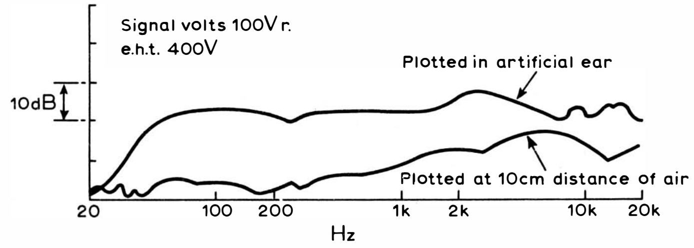

Fig. 16. Comparison of response in open air to that in artificial ear.

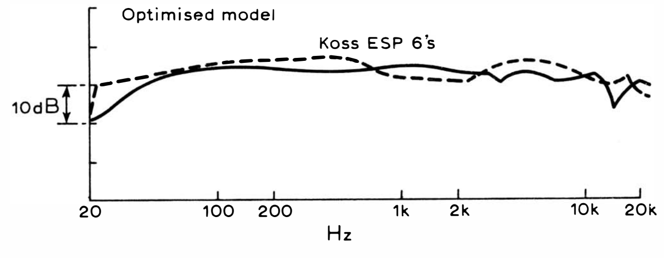

Fig. 17. Comparison of best earphone constructed with the published response of a Koss ESP6 unit.

cized p.v.c. sheeting 15 μ in thick, sheet resistivity $10^9\ \Omega$.

Safety

There are no uninsulated connections carrying high voltage near to the ear. Provided the connections at the signal generator are also well insulated, there is no danger of a fatal shock. There is always the danger of the diaphragm splitting, but even if it were to lacerate and protrude from a fixed plate, it would come up against the polyurethane foam the earphone is lined with. (This avoids cavity resonances in the sound conveyed to the ear, as well as insulating the ear.) If the diaphragm managed to touch the ear, then in the worst case at least $10^8\ \Omega$ on the film would allow only 3.5 μA to flow through the body, even assuming the body to be a dead short!

Suggested improvements

In order to achieve a broad frequency response it is essential to have slack suspension, and a low mass radiator. The first has been achieved by the use of a diaphragm which can be under quite high stress on its own plane, whilst a relatively low force can cause deflection in a transverse direction. In this design the mass of the radiator is no more than that of a layer of adjacent air a few millimetres in thickness. This could further be reduced by using a film resistive by manufacture.

The effect of resonances in this particular shape of diaphragm has not been investigated as the response curve does not indicate trouble of this kind. Three final points are worth making:

(a) The behaviour of the charge on the film is still largely unexplained as is the levelling off of the response with greater than 600 V on the diaphragm;

(b) Double-sided boards which prevent warping, along with more sophisticated construction techniques, should yield a system of adequate acoustic output using much smaller signal and bias voltages; and

(c) The quantities of different types of distortion present could be measured. Results obtained and listening tests indicate their virtual absence at low sound levels.

APPENDIX A

Measuring the response of the earphone on the ear

Without elaborate equipment, such as a probe microphone, this is difficult to do. Furthermore the earphones under test were not always safe to wear. For these reasons the ear was simulated for the tests. Artificial ears are readily available, and commonly have a volume of 6 cubic centimetres. The volume enclosed by the transmission tunnel is nearly twenty times this, and the addition of the ear's volume makes little difference to its response. The B & K microphone used for the tests was one inch in diameter, about the same as the opening to the ear. The flat wooden plate used for holding the microphone was lined with polyurethane foam, to simulate the coefficient of reflection of the skin.

The conventional B & K frequency plotting apparatus was then set up, and a constant peak-voltage sine-wave output fed to one plate with the other earthed. The inner electrode is maintained at, say 400 V by an h.t. supply. The frequency is swept continuously throughout the audio range 20–20,000 Hz, synchronized to a chart recorder into which the output of the microphone amplifier is fed.

Measuring diaphragm surface resistivity

Apply 250 V d.c. across two electrodes one inch long and one inch apart. The current flow is measured. Sufficient accuracy was obtained by quoting the result as $P \times 10^N\ \Omega$, where both P and N are integers.

APPENDIX B

The electro-mechanical analogy

This is employed to determine the output expected from the earphones, and the frequency response expected. The calculations performed assume values either already determined for the final model or values of the materials readily available.

Fig. 18 gives the equivalent mechanical circuits of the earphones, where the mass m is the mass per unit area of the diaphragm. The spring S is the suspension of the diaphragm in the transverse direction. The damping, $2R_m$ in the centre frequency band, is due to the impedance of the air. F_o is the peak force per unit area on the diaphragm.

Employing the electrical analogy of this circuit gives us Fig. 19. The mass per unit area becomes an inductance of M henries. The suspension becomes a capacitance of S^{-1} farads. The damping becomes a resistance of $2R_m\ \Omega$, and the force a voltage of $F_o \sin \omega t$ V.

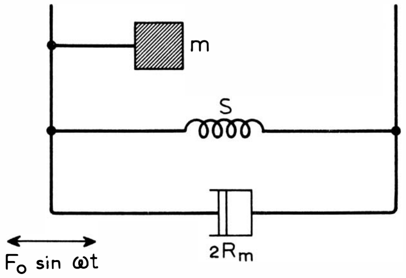

Fig. 18. Equivalent mechanical circuit of earphone.

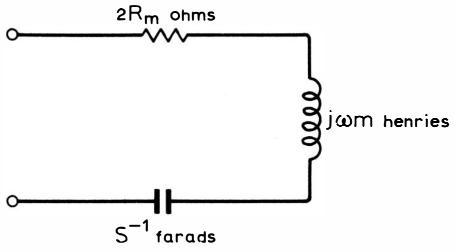

Fig. 19. Circuit given by the electro-mechanical analogy.

We know that:

$$M = 2{\cdot}4 \times 10^{-2}\ \mathrm{kg}\ m^{-2}\ \text{(Vitafilm)}$$
$$2R_m = 2\,\rho c$$
$$= 820\ \text{Rayl in the mid-frequency band.}$$

S cannot be easily measured *in situ*, but a comparison with a conventional 4 inch loudspeaker indicated the same order of magnitude. It is calculated accurately knowing the free resonance to be at 55 Hz.

From Fig. 19 we know:

$$I = \frac{F_o \cos \omega t}{\left(2{\cdot}4 \times 10^{-2}\, j\omega + \dfrac{S}{j\omega} + 820\right)}\ \text{amps,}$$

and that at resonance I is real.

Hence

$$2{\cdot}4 \times 10^{-2}\, j\omega = \frac{S}{j\omega},$$

giving $S = 2{\cdot}4 \times 10^3$ newtons per metre. Because power $\propto$ current^2, the -6 dB points are given by

$$\frac{S}{\omega_L} = 820 \qquad \therefore\ \omega_L = 3$$

$$\omega_h m = 820 \qquad \therefore\ \omega_h = 35{,}000.$$

Therefore the -6 dB points are expected to be at ·5 Hz and 6000 Hz. In the region between these two points the movement of the plate is opposed only by the resistance of the air, so that the device is almost 100% efficient.

A light, thin material, such as that from the Borden Chemical Company considerably extends the flat response.

In order to determine the expected output, the equation $F_o = qE_o$ is utilised. The charge per unit area, q, is determined from the expression:

$$q = \frac{C \times V_{dc}}{\text{area}} = \frac{2\epsilon_o V_{dc}}{d},$$

where V_{dc} is the voltage applied to the diaphragm, and d is the thickness of the spacers:

Hence

$$F_o = \frac{2\epsilon_o V_{dc}}{\text{area}} \times \frac{v_o}{2d}$$
$$= 1{\cdot}95 \times 10^{-2}\, v_o\ \text{newtons per metre}^2$$

A loudness of 100 dBm is considered adequate, whence $F_o = 2$ newtons per metre^2.

This is achieved by signal voltages V_o of the order of 100 V in the region 6 kHz to 10 kHz. This is not a signal voltage sufficient to cause ionization of the air with 350 V on the diaphragm.

A suitable amount of the recommended plastic film, made by the Borden Chemical Company, will be sent from the *Wireless World* editorial department to any reader on receipt of *two* 2½p postage stamps.

Aquadag can be obtained in 75g jars, from stockists of the Acheson Colloids Co. products. It costs 22p (+10p packing and postage) from Ferguson and Timpson Ltd, 7–9 Sebert Road, Forest Gate, London E.7.