Full-Range Electrostatic

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It is now well known that the push-pull electrostatic loudspeaker is capable of a quality of reproduction far in advance of that obtainable from the moving-coil system. So far as the authors are aware previous literature on the push-pull condition and practical attempts at the construction of push-pull loudspeakers[1,2] have been on the assumption that construction will be as shown in Fig. 1. Hunt[3] (pp. 167-212) has given a detailed analysis of this transducer system and further contributions have been made by Walker[4], Cocking[5] and Nuttall[6].

In the course of research and development on full-range electrostatic loudspeakers the authors have discovered that an alternative method of construction has theoretical and practical advantages.

It will first be necessary to consider briefly the construction of Fig. 1. The active element consists of a very thin film of plastic material (D) stretched midway between two insulated and perforated metal plates (P_1 and P_2). The gaps P_1D and P_2D allow movement of the diaphragm, which *must* have high resistivity in ohms per sq. centimetre. The alternative arrangement of inserting a very high resistance (such as R in Fig. 1) has been shown in previous literature, the stated purpose being to prevent the electrostatic charge on the moving diaphragm from varying during the lowest audio-frequency cycle to be reproduced. This is an impracticable solution in a *full-range* electrostatic loudspeaker, the reason being that the capacitances will be small enough to necessitate R being of the order of thousands of megohms. If the full d.c. potential is to be applied to the diaphragm then the insulation must be in the region of many thousands of megohms, and this is impracticable with normal humidity variations.

Let us examine some aspects of the mounting of the diaphragm of Fig. 1. The diaphragm must be tensioned to give a positive stiffness sufficient to counteract the negative stiffness or force resulting from the constant charge. The acoustical loading on either side of the diaphragm is low at low frequencies. With the thin, light plastic materials at present available for use, the elastic restoring force may not be sufficiently stable with respect to time to prevent eventual collapse. Of course, greater stability can be obtained by sub-dividing the diaphragm into smaller areas bounded by supports, and better acoustic impedance matching and directivity may be obtained by making the diaphragm vibrate in the end of a long tube[7-10], and in this case the radiation impedance for the loudspeaker will be approximately the same as if it were mounted in an infinite baffle. The directivity pattern can also be altered by mechanical and acoustical treatment in the long tube. At first glance it appears that by these means one can avoid the use of the type of cabinet so essential for dynamic loudspeakers, but the work involved in production is complicated and little less expensive than a cabinet.

The foregoing considerations led the authors to the new method of construction shown in Fig. 2. The loudspeaker consists of an insulated and perforated metal plate fixed rigidly between two stretched thin and light diaphragms, with air backing. Thus, the a.c. signal will be applied on the membranes (D1, D2) and the d.c. potential on the fixed plate (P).

The transformation of electrical energy into mechanical energy involves the interactions between magnetic (in the case of the moving coil transducer) or electric (in the case of electrostatic, electrostrictive and piezoelectric transducers) fields and matter. The present theoretical concept is based on any of these physical effects since all types of electro-acoustic transducer follow the reciprocity law. Table 4.8 of ref. 11 shows the general relationships for these electro-mechanical transducer principles. It must be remembered that in the case of the moving-coil transducer the force per unit current is a function of the inductance and of the negative stiffness resulting from the steady magnetic field, and the solution therefore entails the concept of "motional impedance." But, in the case of the electrostatic transducer the force per unit voltage is a function of the capacitance and of the negative stiffness resulting from the steady electrostatic field, and hence the analysis can best be carried out using the concept of "motional admittance"[3] (p. 202), particularly when considering light plastic diaphragm materials comparable to the density of air.

We know that a mechanical force f produces a particle velocity u when applied over a transducer surface S. If we consider plane compressional waves in a medium of low viscosity, then we have $pS/u = \rho_a c_a S = Z_R$ = mechanical radiation resistance (for lossless medium), where $\rho_a c_a$ is the impedance of the medium (air), and p is the pressure.

We can draw now the equivalent circuit of an air-backed transducer which may take the form of Fig. 3, in which L = equivalent inductance $= M/4t_r^2$, where M = motional mass and t_r = transformation factor; C = equivalent capacitance, where K = motional stiffness; $R_m = Z_R/4t_r^2$, and C_0 = clamped electrical capacitance.

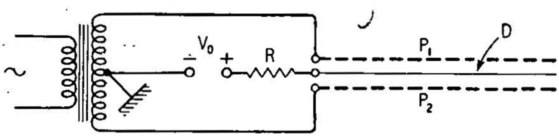

Fig. 1. In the majority of push-pull electrostatic loudspeakers a central diaphragm vibrates between perforated fixed outer electrodes.

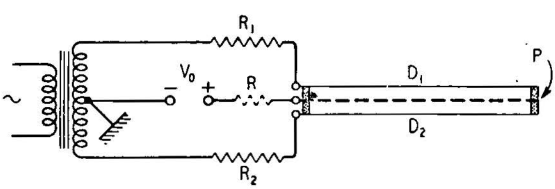

Fig. 2. Alternative arrangement of electrodes offering many advantages both in design and manufacture.

SEE CORRECTION P. 528

Loudspeakers

A New Approach to Practical Design

We know that the mechanical Q of the transducer plays an important part in controlling the frequency response of the radiated power. The calculated value of the mechanical Q is generally lowered owing to the mounting loss of the transducer. Thus mounting is very important, since this additional damping reduces the intensity of the sound radiation. We know that it is possible to represent mechano-electric networks either by the sum of admittance or by the sum of impedance components (velocity and current as independent variables), and this so-called " duality " behaviour[3, 12] plays an important part in the analysis of complex electro-acoustic systems. An example is the operation of a spring[11] (a simple harmonic motion device).

Let us now study the vibration of a stressed membrane which will be applicable to the motion of our diaphragms in Fig. 2. Morse[13] has dealt in detail with the vibration of a stretched membrane, and he has shown that the shape of the boundary line on which the diaphragm is stretched has considerable effect on the solution of the equation, which is beyond the scope of this paper. One of his classic examples is a kettledrum, which we will consider briefly as it is applicable to our loudspeaker design. Striking one of the stretched membranes causes alternating compression and expansion of the enclosed air, which exerts force on both membranes and modifies their modes of vibration. When the velocity of transverse waves in the membranes is low compared with the velocity of sound in air, then the effect of the motion of one part of the membrane transmits very rapidly through the air to affect the other parts, and so, on the whole, the reaction of the air is uniform over the membrane's surface. When the membrane vibrates, due to the adiabatic pressure-volume variations the excess pressure is represented with a negative sign, since this pressure always opposes the displacement of the diaphragm. The load offered to the diaphragm is expressible as a resistive term (additional reactive load is added when the mass of the diaphragm is not negligible). The resistive term varies with frequency, except when the speed of sound in the medium is less than that in the membrane, in which case the resistance is constant ($= \rho_a c_a$, ρ_a being the density of the air and c_a sound velocity in air).

The foregoing physical phenomena can be applied to the design of a modern condenser microphone and, remembering Rayleigh's and Helmholtz' reciprocity theorems and also the acoustical principle of similarity[9], we know that these phenomena will be equally applicable to the construction of our full-range electrostatic loudspeaker. Considering the microphone, we must know the driving force due to the incident wave (uniform, approximately, over the diaphragm), and the reaction force per unit area of the medium (both sides of the membrane), the latter being proportional to the average displacement. The proportionality factor contains the specific acoustic impedance term of the medium. The resistive part of this impedance consists of (1) the radiation resistance of the air next to the outer part of the membrane, and (2) the resistance due to reaction offered to the side facing the inside of the microphone case containing small holes (viscous friction is produced with the motion of air through these holes). The reactive part of the impedance due to the outer air is masslike (i.e., positive reaction) and that due to the air inside is stiffness controlled. The motion of the diaphragm is stiffness controlled when the frequency of mechanical resonance lies near the upper limit of the frequency range. To achieve this a metallic diaphragm must be tensioned, limited by the tensile strength of the metal. In the case of a non-metallic diaphragm of low tensile strength, resonance will occur too low in the frequency range unless means can be found to bolster up the stiffness of the material. This can be done[14, 15] by a construction similar to Fig. 2, but omitting an electrical connection to one diaphragm. Assuming that the boundaries are air-tight, the trapped air serves the acoustic purpose of providing the necessary stiffness to the working diaphragm.

We have applied the foregoing principles to the

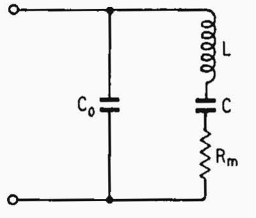

Fig. 3. Electrical analogue of a loudspeaker with the electrode arrangement of Fig. 2.

construction of a full-range electrostatic loudspeaker,* which takes the form of Fig. 2. Consider the static condition: when the polarizing potential is applied the charge is constant over the entire surface of the central conducting electrode, because it is effectively infinitely rigid. Both diaphragms move small equal distances towards the central electrode, and there is no unbalancing of the two capacitances; therefore the balanced push-pull condition is maintained. One important advantage of our construction is that we can dispense with R (shown dotted) altogether, without altering the operation of the loudspeaker; because the charged plate is not moving, there is no necessity for a large RC constant. The problem of achieving resistance and insulation values of thousands of megohms is thereby eliminated. Of course, a low, practical value of R can be inserted as a protective device.

The plastic diaphragms in our design are given outside resistive coatings, the values of these being designated R_1 and R_2 in Fig. 2; therefore they are not external physical resistors. This construction prevents migration of charge, and also gives us a built-in RC transmission line offering a partial solution to the variable-area requirement necessary in a full-range loudspeaker.

On applying the polarizing potential, in the absence of a signal, the behaviour of the diaphragms can be studied under two conditions: (1) when the interior air cavity is perfectly air-tight, which (if it can be practically realized over a long period) necessitates calculations based on innumerable

* Patent applied for.

atmospheric variations; and (2) when a pinhole duct is deliberately introduced to allow for atmospheric pressure equalization. We will deal here only with condition 2. The force of attraction between the perforated plate and one diaphragm can be represented by: $F = \xi V_0^2$ where ξ is a constant.

Consider now the dynamic conditions when a signal voltage is applied, comprehending that the pinhole introduced to allow for atmospheric pressure equalization will have negligible effect at any audio-frequency on the stiffness of the enclosed air, and therefore on the damping effect of the resonant modes of vibration of the diaphragm. It is to be noted here that the displacement of the diaphragms will be due only to the magnitude of the constant charge on the fixed plate and the a.c. field resulting from the signal voltage between the diaphragms. Assuming e and e' to be the maximum values of the signal and ω and ω' their respective angular velocities, we can write the Fourier series (for the force between direct and alternating voltages) as:

$$\begin{aligned} f &= \xi(V_0 + e \cos \omega t + e' \cos \omega' t)^2 \\ &= \xi[(V_0 + \tfrac{1}{2}e^2 + \tfrac{1}{2}e'^2) + \\ &\quad \tfrac{1}{2}(e^2 \cos 2\omega t + e'^2 \cos 2\omega' t) \\ &\quad + ee'\{\cos(\omega + \omega')t + \cos(\omega - \omega')t\} \\ &\quad + (2V_0(e \cos \omega t + e' \cos \omega' t)] \\ &\qquad \text{(on expansion)} \quad \ldots \quad \ldots \quad \ldots \quad (1) \end{aligned}$$

The first term of equation (1) is a steady component whose function is to displace the diaphragm from its stationary position; hence it does not contribute to the reproduction of sound. The second term will produce second harmonic distortion, for we can see that it contains terms with frequencies double those of our applied frequencies. Similar distortion in the sound output will occur with the third term containing the sum and differences of the applied frequencies, so it is only the fourth term, which contains the applied frequencies, that we desire to be reproduced. Obviously, for low acoustic distortion we must make $V_0 \gg e$ and e', so that $2V_0e$ and $2V_0e' \gg e$, e', $\tfrac{1}{2}e^2$ and $\tfrac{1}{2}e'^2$. The same argument regarding the force can then be applied to the other diaphragm, remembering that the displacement and the a.c. signal change sign on passing from one side to the other. Thus not only the efficiency, but also the quality of sound output is dependent on a high polarizing potential, particularly at low frequencies, since amplitude and sound energy is directly proportional to V_0 and V_0^2 respectively. Note that this loudspeaker acts as a doublet. Note also that we have not taken into account, for the sake of simplicity, the non-planar shape of the vibrating diaphragms and the corresponding variation of electrostatic force on different parts of the diaphragms.

As previously stated, the air enclosed by the diaphragms acts to stiffen them, and this helps towards an extended low-frequency response because the need for highly tensioning the diaphragms is reduced. The stiffness behind the diaphragms is dependent to some extent on the dimensions of the perforations in the central electrode. Changing the dimensions, and hence the air resistance, will alter the displacement and response curves, as shown by Morse (ref. 13, p. 197).

The advantages of this system are considerable. Harmonic distortion, transient distortion and frequency deviations are all *very* much lower than on moving coil systems. The construction is simple, and reliable; the dimensions need not be unreasonably large; the diaphragms need not be very tightly stretched; they are visible for inspection, and they form a dust-proof barrier protecting the highly-charged central electrode.

In the previous convention of Fig. 1 the single diaphragm can be properly tensioned in the first instance on one of the perforated plates, but when the second plate is applied it is difficult to ensure exact coincidence of the spacers, and also the diaphragm is not accessible for inspection or adjustment. There is also the serious practical difficulty of holding the spacers on the two plates in intimate contact with the diaphragm.

The authors hope that the wide application of their ideas will speed the availability of better and cheaper high-fidelity loudspeakers, for it can be stated that the cost will be considerably lower than the best moving-coil systems, whilst the overall improvement in listening quality is demonstrably beyond question.

Thanks are due to our colleagues E. H. Ashley and P. H. Biggs for their practical help in constructing many development models.

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Solid "Electrolytic" Capacitor

A METHOD of eliminating the electrolyte in tantalum oxide capacitors is reported by Bell Telephone Laboratories. After formation of the oxide film on the surface of the sintered tantalum anode in the usual way, the electrolyte is removed and replaced by successive deposited layers of manganese dioxide, carbon and lead alloy. The barrier layer established by tantalum, tantalum oxide and manganese dioxide is said to have high stability with time and temperature and gives a capacitance of 500 μF per cubic inch for a voltage rating of 35.

Arrangements for manufacture are in the hands of the Western Electric Company.

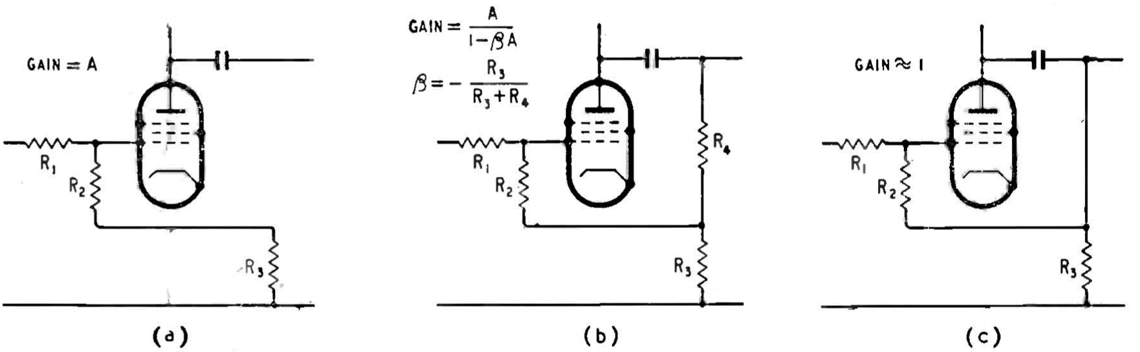

Fig. 5. Equivalent circuits of Fig. 4 at (a) low, (b) mid-band, and (c) high frequencies.

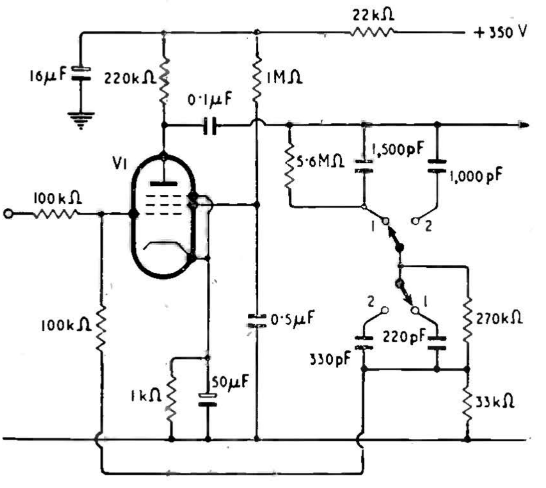

Fig. 6. Complete equalizer for B.S.S. 1928 : 1955 characteristics. V1 may be Z729, EF86, 6BR7, etc. Mid-band gain approx. 10. Switch positions: 1—B.S.S. Coarse Groove, 2—B.S.S. Fine Groove.

there is a bass fall and a second time-constant, t_2, defines this. At low frequencies the response does not fall away indefinitely because a bass rise of time-constant, t_3, is included. Table 1 gives the values of the time-constants as set out in the Standard.

Replay Equalizers.—A replay equalizer could be constructed using passive networks chosen to give the appropriate time-constants, remembering that a rise in recording characteristic must be matched by a fall in replay characteristic. The three networks must be cascaded in such a manner that they do not interact one with another; alternatively a single passive network incorporating all the necessary time-constants may be used. Such networks are shown in Fig. 3.

It is preferable, however, to use a valve with selective feedback to provide equalization and to incorporate the time-constants in the feedback loop. Fig. 4 shows such a circuit. In Fig. 5 are shown the three circuit conditions at low, mid-band and high frequencies. Notice that, as Fig. 5(a) shows, the gain at low frequencies, where maximum boosting is required, is limited to that available from the valve. In this way the required bass fall is provided without actually including a further time-constant: the ratio of the effective time-constant of this bass fall to that of the bass rise is the ratio of the maximum gain of the stage to that at mid-band, where a moderate amount of feedback is applied as shown in Fig. 5(b). If in a particular circuit this ratio is too great, R_5 may be included to provide a small amount of feedback at low frequencies. In a similar way there is a limitation of the high-frequency attenuation when the condition of Fig. 5(c) is reached, the gain then being unity (if $R_1 = R_2$). However, this undesired limitation is not serious in a properly designed circuit. The actual time-constants are given by $C_1(R_3+R_4)$ for bass rise and C_2R_4 for treble fall.

Fig. 6 shows a circuit with suitable component values. Note that the switch may have as many positions as desired so as to incorporate equalization for older recordings. The load on this stage should not be heavier than 1 megohm or the available gain will be reduced and full bass boost will not be provided. If the stage must be more severely loaded it is possible by reducing R_2 to obtain the necessary bass boost at the expense of overall gain.

DO YOU KNOW?

THE length of the dipole for a Band II aerial?

The relationship between m.k.s. and c.g.s. units?

The address of the International Amateur Radio Union?

The base connections for a LN309 valve?

What external resistance is needed in series with a 25-volt meter (1,000 ohms/V) to read voltages up to 500?

If a licence is required to operate a transmitter for the control of a model?

The answers to these and innumerable other technical and organizational questions can be found in the 1957 *Wireless World* Diary—the *vade mecum* of all who have an interest in radio.

The Diary, now in its thirty-ninth year of publication, includes, in addition to the usual week-at-an-opening diary pages, an eighty-page reference section. It is obtainable from booksellers and newsagents, price 6s (leather) and 4s 3d (Rexine) including purchase tax. Overseas prices are, respectively, 5s and 3s 6d, plus 2d postage.

"Full-Range Electrostatic Loudspeakers."—The third line from the bottom of column 2 of p. 486 of the October issue should read ". . . C=equivalent capacitance = $4t_r^2/K$, where K = motional stiffness. . . ."