

efficiency that the receiver would have under this condition, by any method whatever, it is necessary to connect the receiver to a tube having the same acoustic impedance as a tube of this character. This impedance for a tube 2.45 sq. cm. in area is 16.7 c.g.s. units. A tube of finite length but of the same area will have an impedance of this value provided the sound wave reflected at the far end has a relatively small amplitude when it reaches the sending end. To satisfy this condition a tube 50 feet long was terminated in an acoustic resistance unit having an impedance approximately equal to  $16.7 + j16\omega \cdot 10^{-4}$  c.g.s. units. The essential elements of this resistance unit comprised a number of short narrow annular slits; its impedance was determined experimentally by a method described in another paper.<sup>4</sup> As this impedance at low frequencies is practically the same as the characteristic impedance of the tube, the amplitude of the reflected wave in this region is small; at the higher frequencies the reflected wave is attenuated sufficiently in the 50-foot tube to produce a negligible effect on the sending end impedance. This tube with the resistance unit was connected to the receiver during the following series of measurements.

### *Efficiency*

One of the simplest methods of determining the power efficiency of a loud speaker is to measure the electrical impedance, first, when the receiver is in operating condition, and, secondly, when the diaphragm is constrained from moving so that no back e.m.f. is generated. The difference between these impedances is known as the motional impedance.<sup>5</sup> The resistance component of this motional impedance when multiplied by the square of the current gives the power that is generated by the motion of the diaphragm. If there is a negligible amount of power lost in viscosity and mechanical hysteresis, the ratio of the motional impedance to the free impedance can be taken as the efficiency of the receiver, i.e., the ratio of the acoustic power output to the total power input. This method of measuring efficiency is well known to the art, but for most commercial receivers the efficiency is so low that the motional impedance cannot be determined with a high degree of accuracy over an extended frequency range. However, for this receiver we have had no difficulty in determining the efficiency in this way up to 8,000 p.p.s. The values so obtained are given by the circles in Fig. 7.

On account of the uncertainty of the magnitude of the mechanical

<sup>4</sup> Wentz and Bedell, *Bell System Technical Journal*, January 1928.

<sup>5</sup> Kennelley and Pierce, "The Impedance of Telephone Receivers as Affected by the Motion of their Diaphragms," *Proc. A. A. A. S.*, Vol. 48, No. 6, September 1912.

power losses within the receiver it was deemed desirable to measure the efficiency more directly, viz., to measure the actual sound power generated for a given power input.

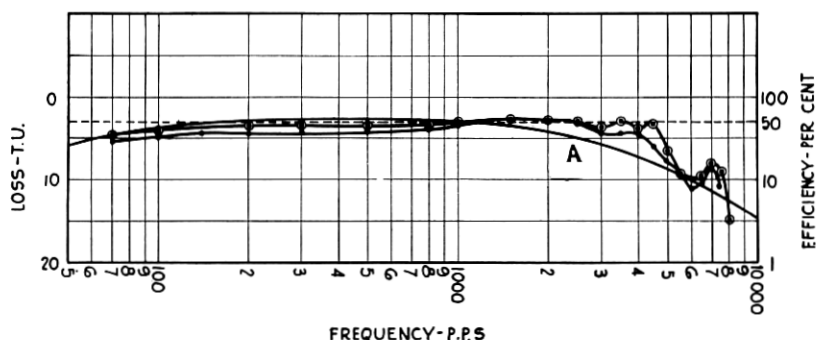


Fig. 7—Efficiency of the receiver.

The power output may be determined directly by measuring the acoustic pressure in the tube at the sending end. In order to measure this pressure an annular slit was provided on the side of the tube a few inches from the receiver as shown in Fig. 8. This annular slit had a

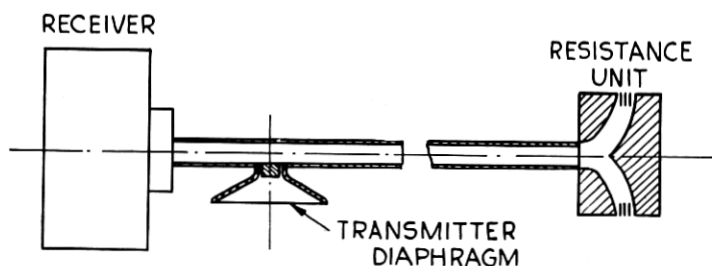


Fig. 8—Arrangement of apparatus for measuring efficiency.

diameter of a quarter of an inch, a width of 0.003 inch and a length of 0.040 inch. A slit of these dimensions has an acoustic impedance about fifteen times as great as the tube, so that it has a negligible effect on the sound wave propagated along the tube. This slit led to a small chamber over the face of the diaphragm of a condenser transmitter. The condenser transmitter was connected to an amplifier and an a.c. ammeter. This combination was previously calibrated, so that from the meter readings the pressure over the slit could be determined.

The input power was determined from the current input and the resistance of the receiver. With this set-up we thus were able to measure both the acoustic power transmitted along the tube, which

is equal to  $\frac{(\text{pressure})^2}{16.7}$  ergs per second, and the power input. The operating efficiency is the ratio of these two quantities. The dots plotted in Fig. 7 give the values of the efficiencies so obtained. These values are seen to agree closely with those calculated from the motional impedance. This agreement shows that the mechanical power losses in the receiver are small.

Curve *A* in Fig. 7 gives the efficiency as calculated from the constants of the receiver by means of the formula given in appendix B, under the assumption that the mechanical impedance imposed on the diaphragm and the air chamber has the same value throughout the whole frequency range, viz.,  $16.7 A^2$  c.g.s. units, where *A* is the effective area of the diaphragm. It is seen that the calculated and measured values are in good agreement except for certain irregularities at the higher frequencies. Whether these irregularities are to be ascribed to the action of the air chamber or to a change in the mode of motion of the diaphragm we are not at present prepared to say.

The curves of Fig. 7 give an efficiency for this receiver of about 50 per cent over a wide frequency range. This efficiency is within 3 T.U. of the possible maximum of 100 per cent. We may remark at this point that it is conceivably possible to build a receiver which will sound louder than one having an efficiency of 100 per cent. If, for instance, a receiver introduces harmonics on account of amplitude distortion, a low frequency driving force may give rise to a tone of higher frequency, where the ear may have a sensitivity many times greater than at the driving frequency. An increase in loudness obtained in this way of course exacts a sacrifice in the faithfulness of reproduction. The difference in loudness between the sound emitted by this receiver and by ordinary commercial types of loud speakers, for the same power input, is considerable, since most of them have an efficiency of less than one per cent for speech frequencies. Not only does this receiver have a high efficiency over a wide frequency range but it is free from any sharp variations in efficiency with frequency, a condition of great importance in the quality of reproduction.

#### *Amplitude Distortion*

Thus far we have discussed only the frequency characteristic of the receiver. There still remains to be considered the proportion of harmonics that are generated by the receiver when supplied with a current of sine wave form. These harmonics are generated when the displacement of the diaphragm is not proportional to the input current. At low frequencies the amplitude of motion for a given power output

is comparatively large and the diaphragm for large powers will be driven beyond the point where Hooke's law holds. At the higher frequencies no trouble is to be expected from this source. With the aid of an electrical filter we have therefore made measurements on the harmonic content in the sound output when the receiver was supplied with a sixty-cycle sine wave current. The values so obtained as a function of the power input are plotted in Fig. 9, where curve *A* is the

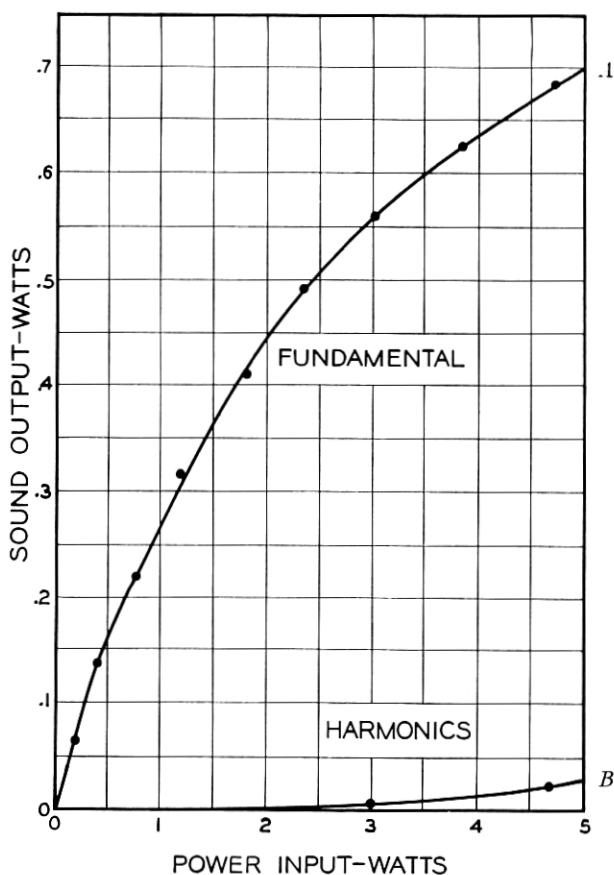


Fig. 9—Power output at 60 p.p.s.

output power of the fundamental tone and *B* that of the higher harmonics. These curves show that even at 60 cycles an output power of 0.5 watt may be obtained without the introduction of higher harmonics to an amount greater than 1.0 per cent. The total power in the harmonics would in this case be 20 T.U. below that in the fundamental

tone. If a horn were connected to the receiver in place of the tube, in addition to the resistance, a mass reactance would generally be imposed on the diaphragm at the lower frequencies. Under these conditions the proportion of harmonics introduced would be still lower than that indicated in Fig. 9.

At the higher frequencies the power output is limited solely by the current-carrying capacity of the coil. At these frequencies the steady power input for a temperature rise of 100 degrees C. is about 30 watts. With an efficiency of 50 per cent the corresponding output would be 15 watts.

After the work described in this paper was for the most part done and as a result of the extremely promising performance of the first models, a design of the receiver built along essentially these lines was worked into a form suitable for commercial production by Mr. W. C. Jones and Mr. L. W. Giles. These receivers are now in commercial use in Vitaphone and Movietone installations. As commercially produced in quantities numbering several thousand, efficiencies of the order of 30 per cent have been realized.

In conclusion, we wish to express our appreciation for the valuable assistance given by Mr. T. F. Osmer in carrying out most of the experimental work described in this paper.

#### APPENDIX A

Consider a diaphragm and connecting air chamber of the form shown in Fig. 1. Assume that the air chamber is of a form such that the cross-sectional area at any distance  $r$  from the center is equal to the throat area of the horn, i.e.,  $2\pi r t = \pi r_0^2$ . This form of connecting air chamber then differs but little from that used in most commercial types of horn speakers. The sound output is in general dependent on the mode of motion of the diaphragm. In most loud speakers this mode of motion varies with the frequency. However, let us assume that we have a paraboloidal displacement at all frequencies. The velocity at any radial distance may then be represented by

$$\xi = \xi_0 \left[ 1 - \left( \frac{r}{R} \right)^2 \right] e^{i\omega t}$$

if  $\xi_0 e^{i\omega t}$  is the velocity at the center.

Under the assumed conditions, the sound transmitted through the throat is very nearly the same as that which would be transmitted along the positive direction through the tube sketched in Fig. 10, which extends to infinity in both directions, provided the portion of the wall

of the tube from  $a'$  to 0 and from  $a$  to 0 had a radial velocity equal to

$$\frac{2\pi r}{2\pi r_0} \cdot \xi_0 \left[ 1 - \frac{r^2}{R^2} \right] e^{i\omega t}.$$

The velocity potential at a point,  $P$ , at a distance  $y$  from  $a$ , if  $r_0$  is small compared with the wave-length of sound, is then

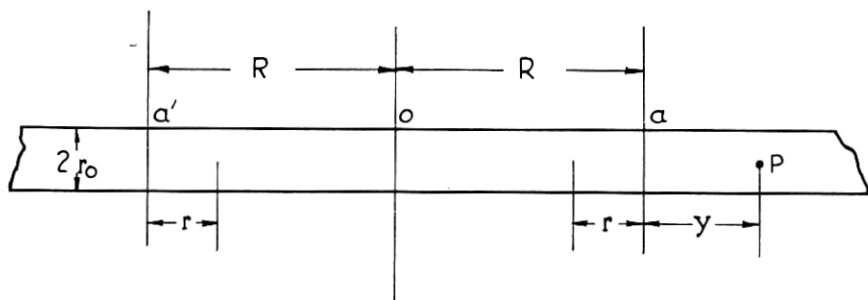


Fig. 10.

$$\begin{aligned} \varphi_y = -i \left[ \int_0^R \frac{\left[ 1 - \frac{r^2}{R^2} \right] r}{r_0^2 k} e^{ik(ct-y-r)} dr \right. \\ \left. + \int_0^R \frac{\left[ 1 - \frac{r^2}{R^2} \right] r}{r_0^2 k} e^{ik(ct-y-2R+r)} dr \right] \xi_0, \end{aligned}$$

where  $c$  is the velocity of sound and

$$k = \frac{\omega}{c}$$

or

$$\varphi_y = A \frac{2\xi_0 e^{ik(ct-y-R)}}{-ir_0^2 k^3},$$

where

$$A \equiv \left( 1 + \frac{6}{k^2 R^2} \right) \cos kR + \left( 2 - \frac{6}{k^2 R^2} \right).$$

If we take the real part of

$$\rho \frac{d\varphi_y}{dt},$$

we get the instantaneous pressure at the point,  $P$ , where  $\rho$  is the density of the air. This gives

$$p_y = \frac{-2\xi_0 \rho c}{r_0^2 k^2} \cdot A \cos k(ct - y - R).$$

If we substitute  $r$  for  $-y$ , this expression gives the instantaneous pressure on the diaphragm at the radial distance  $r$  from the center. The instantaneous power delivered by the diaphragm is then

$$W = -\frac{2\rho c A}{r_0^2 k^2} \xi_0 \cos kct \cdot 2\pi \int_0^R \left(1 - \frac{r^2}{R^2}\right) \cos k(ct + r - R) \cdot r dr$$

$$= \frac{4\pi A \rho c}{r_0^2 k^4} \xi_0^2 [A \cos kct + B \sin kct] \cos kct,$$

where

$$B \equiv \left(1 + \frac{6}{k^2 R^2}\right) \sin kR - \frac{6}{kR}.$$

The effective force on the diaphragm is then

$$F = \frac{W}{\xi_0 \cos kct} = \frac{4\pi A \rho c \xi_0}{r_0^2 k^4} [A \cos kct + B \sin kct].$$

The effective resistance is therefore

$$\frac{4\pi A^2 \rho c}{r_0^2 k^4}$$

and the effective reactance

$$- \frac{4\pi \rho c A B}{r_0^2 k^4}.$$

Expressions for the resistance and reactance for other modes of motion of the diaphragm may be obtained in a similar manner.

## APPENDIX B

The motional resistance,  $R_m$ , of a moving coil receiver is equal to

$$\frac{B^2 l^2 (r + r')}{(r + r')^2 + \left(m\omega - \frac{S}{\omega} + x\right)^2} \text{ ohms,}^6$$

where  $B$  is the average flux density,

$l$ , the length of wire in the receiving coil,

$r + jx$ , the mechanical impedance imposed on the diaphragm by the horn through the coupling air chamber,

<sup>6</sup> Kennelley and Pierce, loc. cit.

$r' + j\left(m\omega - \frac{S}{\omega}\right)$ , the mechanical impedance of the diaphragm aside from that imposed by the horn.

If  $r'$  is negligible, the efficiency of the receiver, i.e., the ratio of power output to power input, is

$$\eta = \frac{R_m}{R_m + R_d},$$

where  $R_d$  is the resistance of the coil when its motion in the field is completely damped.