Notes on the Development of a New Type of Hornless Loud Speaker

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Synopsis.—*The paper describes a series of tests directed to the evolution of a loud speaker, free from resonance. Various types of sound source were tried. For the most part horns were avoided. Diaphragms, when employed, were either so light and stiff that their natural resonance was above the essential frequency range, or so flexible that their resonance was below the lowest important acoustic frequency. Best results were obtained with the latter type, and it is shown on theoretical grounds that a small diaphragm, the motion of which is controlled by inertia only, and located in an opening in a large flat wall, will give an output sound pressure proportional to the actuating force, independent of frequency. It should be possible to make an ideal sound reproducer on this principle. A practical loud speaker which approximately fulfills the above conditions has now been evolved. It consists of a flexibly-supported paper cone actuated by a coil in a magnetic field and provided with a baffle. As compared with ordinary loud speakers, this instrument radiates much more of the low tones and more of the very high frequencies which makes for clearer articulation.*

The extension of the range of response of the loud speaker to higher and lower frequencies, makes defects in the remainder of the system more noticeable, particularly roughness and blasting due to overworked amplifiers. It is, therefore, important that the amplifier used with the new loud speaker be designed to have ample capacity.

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Initial Tests With Non-resonant Types

SEVERAL years ago tests were undertaken in the Research Laboratory of the General Electric Company, to ascertain whether or not it would be possible, by sacrificing sensitivity, if necessary, to produce a loud speaker free from the most objectionable of the distortion which characterizes loud speakers in general.[2]

Amplifiers and amplifier tubes had been developed to a point where there was no difficulty in obtaining voice currents of any required magnitude, practically free from distortion. Aperiodic microphones and condenser transmitters were in use in broadcasting station studios.[3] The availability of these comparatively new tools and the fact that in the matter of distortion the loud speaker was the weakest link in the chain of apparatus involved in transmission and reproduction of speech and music, appeared to justify a renewed attack on the problem. Even though it should be found that a large and expensive amplifying system was necessary, owing to sacrifice of sensitivity, it was felt that there would be many applications of a loud speaker of high quality. Happily in the later designs it was found that the anticipated sacrifice of sensitivity was not necessary.

The worst distortion in the ordinary loud speaker is due to horn-resonance and diaphragm-resonance. To eliminate the horn-resonance, it was proposed to abandon the horn. To avoid the diaphragm-resonance we might, for example, eliminate the diaphragm, by using a "talking arc;" or we might use diaphragms in which the resonance frequencies were above or below the working range.

One of the first undertakings was to build a resistance-capacity-coupled amplifier in which the final stage was a tube having an oscillator rating of 250-watts output. With a 1500-volt plate supply, this amplifier could deliver about 70 milliamperes of sine wave current at 200 volts, with practically no wave-form distortion, and it was possible to test some very insensitive devices. Among the things tried were:

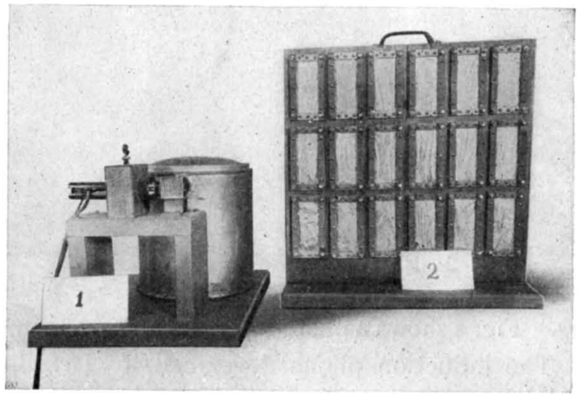


Fig. 1—Siren and Gold-Leaf Thermo Phone

1. A gold leaf thermophone with an area of about one-half square foot, shown in Fig. 1. The voice current superimposed on a direct current causes temperature fluctuations in the gold leaf. The adjacent air expands and contracts and produces sound waves.

2. Various designs of electrostatic loud speakers with large diaphragms: In these the diaphragm is a thin sheet of conducting material, actuated by the electrostatic attraction between it and an electrode placed close to it. Fig. 2 shows a model in which the electrodes were of felt, painted with graphite and separated by two sheets of varnished cambric.

3. A siren, shown in Fig. 1: Instead of moving a diaphragm to set up air waves, the voice currents are

1. Both of the Research Laboratory of the General Electric Co.

2. A general discussion in the form of a symposium on the loud speaker problem is published in *Proceedings* of the Physical Society of London, Vol. 36, Parts 2 and 3, Feb. & Mar., 1924.

3. The construction and calibration of condenser transmitters are described by F. C. Wente in the *Physical Review*, July, 1917, and May, 1922. The theory of air damping as applied to the condenser transmitter is discussed by I. B. Crandall, *Phys. Rev.*, June, 1918.

Presented at the Spring Convention of the A. I. E. E., St. Louis, April 13-17, 1925.

made to operate a delicate throttle-valve which controlled the amount of air issuing from a jet. This principle is employed in the "Creed Stentorphone" evolved by Gaydon and manufactured by Creed of Croyden, England.

4. An agate cylinder machine, depending on varying the frictional force between a rotating drum of polished agate and a piece of metal attached to the diaphragm: This principle was first applied by Edison[4] using chalk cylinders, and later by Johnson and Rahbeck who used agate[5]. A modified form of frictional machine, called the "Frenophone," has recently appeared[6].

5. A talking arc.

6. Multiple unit area devices, made up of a large number of similar magnetic telephones, as shown in Fig. 3.

7. Combinations of several horn instruments, having different characteristics, so that each supplements the others. Fig. 4 shows a photograph of this arrangement.

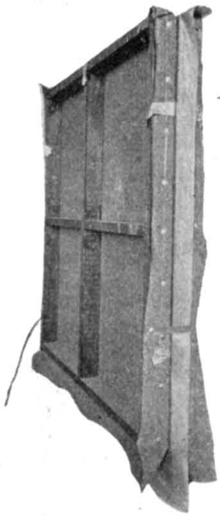


FIG. 2—ELECTROSTATIC LOUD SPEAKER

8. The induction phone developed by Dr. C. W. Hewlett[7].

This is illustrated in Fig. 5. The diaphragm is a thin sheet of aluminum loosely supported between two pancake-type coils, wound with suitable venting spaces. Direct current is passed through the coils in such a direction as to give a radial field in the region of the diaphragm, and the voice current circuit is connected so that both coils act as primaries to induce currents in the diaphragm. The resulting force can be made to be almost uniform over the whole diaphragm.

9. Various designs of small diaphragm moving coil instruments.

Fig. 6 shows a number of instruments set up for comparison.

Of the possibilities, some were dropped after one or two experiments, while the more promising types were the subjects of considerable development. The electrostatic phone is capable of giving very fine quality reproduction, but owing to the low breakdown strength of air, only a small force can be applied to the diaphragm and a very large area is required to give a reasonable volume of sound.

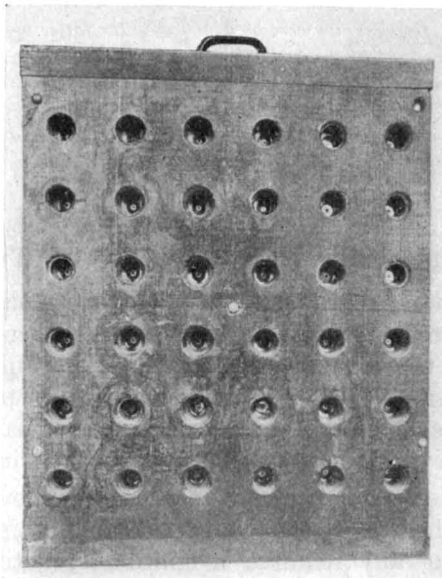


FIG. 3—MULTIPLE-UNIT LOUD SPEAKER

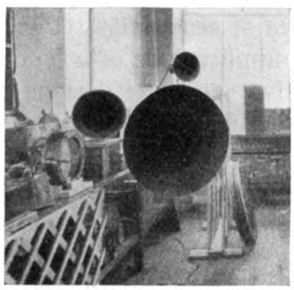


FIG. 4—TRIPLE-HORN LOUD SPEAKER

CHARACTERISTICS OF LARGE AREA DIAPHRAGMS

One of the first tests was an attempt to obtain the equivalent of a large area diaphragm by placing a number of small units close together. The panel is shown in Fig. 3. A single telephone receiver without a horn, gives entirely inadequate radiation of the low tones. The horn helps to bring out the low tones but introduces resonance. Placing a number of telephones in close proximity with their diaphragms moving in

4. British patent No. 2909,—1877.

5. Described in *Zeitschrift fur Techinsche Physik*, 1921, No. 11, also *Journal* I. E. E., No. 61, July 1923, p. 713.

6. Model exhibited at Liverpool meeting of British Association for the Advancement of Science, Sept. 1923. See *Sci. American*, Jan. 1924.

7. *Phy Rev.*, 17, p. 257, 1921. *Phy. Rev.*, 19, p. 52, 1922. *Jour. Opt. Soc. Am.* 4, p. 1059, 1922.

phase also improves the radiation of lower tones without creating any resonance. The multiple unit instrument was a considerable improvement over a single unit with horn. But as the device was first built, the diaphragms themselves were resonant at about 1000 cycles. The next step was the substitution of telephones with diaphragms of steel, 0.0015 in. thick, stretched so tightly that their natural frequency was above 6000 cycles, or practically out of the voice range. When used as head-phones, these receivers gave very fine quality but as a loud speaker the multiple unit device gave undue prominence to the high frequency components of speech. Voices sounded thin and hard. Only after electrical compensation had been introduced by means of the circuit shown in Fig. 7A did the multiple unit loud speaker give a natural reproduction of voice. In other words, while the effect of the large area diaphragm as compared with a small diaphragm was in the right direction in helping the radiation of low tones, as had been anticipated by Rice in proposing this experiment, there was still an accentuation of the high frequencies when the multiple unit loud speaker was used without the compensating circuit.

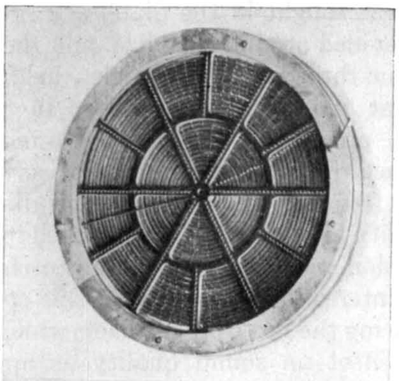


Fig. 5—Hewlett Induction Type Loud Speaker

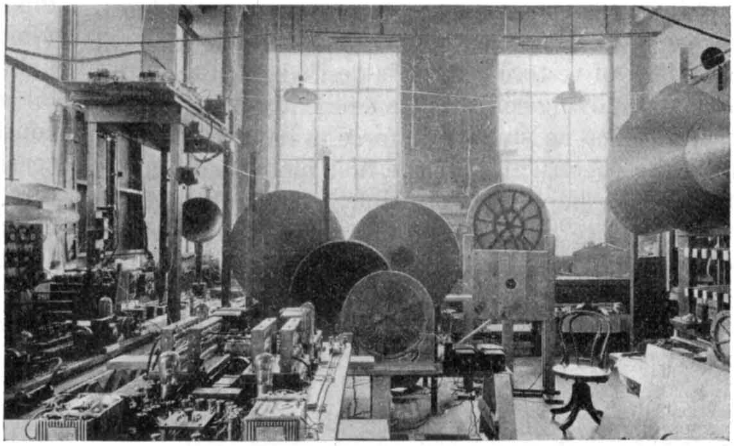


Fig. 6—Loud Speakers Assembled for Comparative Tests

Let us consider from a theoretical standpoint the difference between what makes a satisfactory headphone and what is required for a loud speaker. The ideal sound pick-up, or transmitter, would develop a voltage proportional to the pressure which the sound wave exerts on the diaphragm, whatever the frequency or wave shape. There are in use in broadcasting studios, special microphones and electrostatic transmitters which approximate this ideal characteristic very closely over a wide range of intensity and over a frequency range of from 30 to over 6000 cycles. Amplifiers can be constructed having almost any required amplification ratio, the output currents of which reproduce the input voltage wave with virtually no distortion. The perfect receiver, or loud speaker, must take these amplified voice currents and translate them into air pressures, exactly reversing the function of the pickup or transmitter. The transmitter being equally efficient for all frequencies in the working range, the telephone receiver or loud speaker must convert input current into sound pressure at the listener's ear with equal efficiency at all frequencies. Throughout the remainder of this paper, when a device is spoken of as giving sound radiation independent of frequency, it is to be understood that what is meant is that if a series of pure tones of equal power but varying pitch are produced in a damped room in front of a perfect transmitter with distortionless amplifier, and the output of the amplifier is fed to the loud speaker, the latter will radiate the series of tones with equal power.

In the case of the receiver held to the ear, there is a small cavity between the receiver diaphragm and the ear drum, and, assuming that there is no leakage of air, the pressure which the ear drum feels is proportional to the change in volume of the cavity caused by the deflections of the diaphragm. A diaphragm with natural frequency above the voice range, or, in other words, one in which elasticity and not inertia or damping controls the vibrations, gives a deflection proportional to the magnetic force, or practically proportional to the current through the coils, independent of frequency. Therefore, such a diaphragm gives a sound pressure in the ear proportional to the current supplied to the receiver, provided the receiver is held tight against the ear, and this characteristic is exactly what is wanted for a head telephone. What happens when such an elastic control diaphragm is operated in unconfined air? The simplest case is that of a large area diaphragm radiating plane waves. Here the pressure in the sound wave is proportional not to the deflection of the diaphragm, but to the maximum velocity which it attains, which, for pure tones or sine waves, is proportional to the maximum deflection multiplied by the frequency. Therefore, if we succeeded in obtaining the equivalent of a large area diaphragm by grouping together a number of telephones with tightly stretched diaphragms, the device would still radiate the high frequencies in undue proportion. With the capacity shunt in the amplifier, as shown in Fig. 7A, this discrepancy is corrected.

Test of Small Inertia Diaphragm

At this point, Kellogg suggested using a coil-driven diaphragm with practically no elastic restoring force, so that at low frequencies very large amplitudes could be attained. In an ordinary telephone the stiffness of the

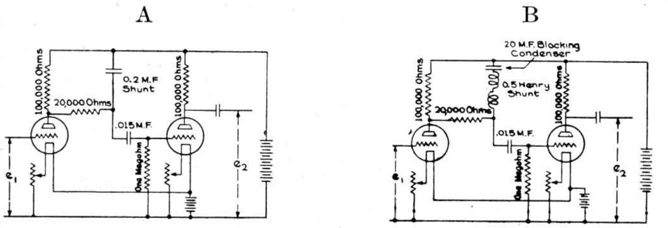


Fig. 7—Compensating Circuits

Type A gives $e_2 = e_1 \times \frac{1}{f} \times$ (Constant)

Type B gives $e_2 = e_1 \times f \times$ (Constant)

f = frequency

diaphragm is depended upon to prevent its sticking to the magnet poles and is, therefore, not suitable where an entire lack of restoring force is desired. On the other hand, the moving coil drive is eminently suited to this purpose since no stabilizing force is required. Fig. 8 shows the construction of the first model built to try out the free diaphragm principle. Not only did this device produce more of the low tones than any previously tried, but it held up remarkably well for the very high notes, not showing any marked resonance. It did, however, have a rough quality in voice reproduction, which was corrected in the later designs.

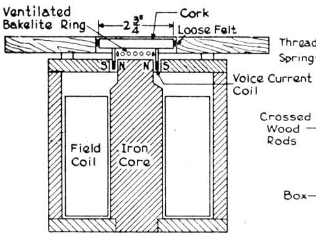


Fig. 8—First Model of Inertia Controlled Diaphragm Loud Speaker

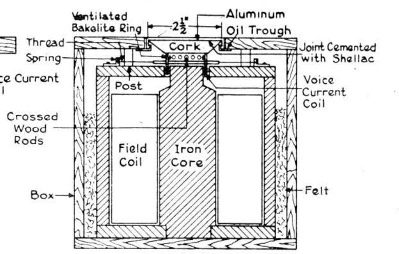


Fig. 9—Improved Design of Inertia Diaphragm, Loud Speaker

Trial of Triple Horn Loud Speaker

The multiple unit horn device, already mentioned and shown in Fig. 4, was first suggested and worked on in our group by Kellogg. It was an attractive possibility, especially in view of the sensitivity obtainable with horns, and the ease with which the balance between high and low tones could be adjusted. For the lower end of the scale, a Baldwin phone with a large exponential horn seemed to be the best combination of available apparatus, while some higher pitched phones with smaller horns took care of the middle and upper ranges. Experiments with this arrangement showed clearly that the three instruments supplemented each other, the combination sounding much better than any one alone, and the consciousness on the part of the listener of the presence of a horn was much less pronounced than in the case of a single horn device. The Baldwin phone would not give sufficiently low frequency output and after a number of attempts to build a suitably low-pitched phone, the conclusion was reached that the most satisfactory low-pitched phone would be one designed along the lines of the moving coil instrument already described. However, when this construction was adopted, no supplementary high pitched instruments were needed.

Improved Designs of Inertia Diaphragm Instruments

Fig. 9 shows the manner of construction of a moving coil instrument designed by Kellogg with a view to avoiding two of the possible causes of the rough quality which had characterized the machine shown in Fig. 8; namely, friction around the edges, and failure of the diaphragm to act as a true piston, or remain flat during vibrations. A maximum of rigidity, combined with light weight, was sought in the diaphragm design, an oil seal was provided around the edge, and the support consisted of four threads at right angles, held in slight tension, so that motion was very free in the axial direction, but practically no sidewise movements could take place. Vibration amplitudes as great as 1/32 inch were frequently observed on this diaphragm. The rough quality was practically eliminated in the new design. Provision was made for boxing in the instrument, and an interesting experience in this connection was that of placing the box over the back, which had the same general effect on sound quality as applying a short horn to the front of the diaphragm. Both helped to bring out the low tones and gave rise to some resonant effects. Bringing out the low tones was due principally to preventing circulation of air between the front and back of the diaphragm. The resonance was in the horn in one case, and in the box in the other. A peculiarity of devices employing very flexibly supported diaphragms is that resonant air chambers behind the diaphragm do about as much harm as resonant cavities in front of the diaphragm, the diaphragm usually taking part in the resonance. Attempts to damp the interior of the box with felt were not entirely successful.

The Use of a Baffle

A happy solution of the problem of preventing circulation was obtained by employing a flat baffle-board, at the suggestion of Rice, who was the first of the group to recognize the importance of the circulation factor in preventing the radiation of low tones. With the flat baffle, no air resonance occurs and both sides of the diaphragm give useful radiation, the total power radiated for a given diaphragm amplitude being nearly four times as great as that radiated when the back of the diaphragm is enclosed.

Definition of Term "Inertia Controlled"

Subsequent experiments were devoted largely to the development of the free diaphragm type of sound reproducer, in which, throughout the essential frequency range, the electrical driving force is expended in accelerating the mass of the diaphragm. We shall speak of such diaphragms as "inertia controlled." A certain amount of elastic restoring force is unavoidable in the supporting system, and consequently the diaphragm must have a natural frequency. But if the natural frequency is below the important acoustic frequency range, the diaphragm may properly be described as inertia controlled. We have obtained best results with natural frequencies below about 70 cycles per second. Higher natural frequencies can be tolerated if the vibrations are well damped.

Theory for Large and Small Diaphragms

Diaphrams may be classified according to their mechanical properties as:

1. Inertia controlled
2. Damped or resistance controlled
3. Elastic controlled
4. Resonant
5. Diaphragms having wave action or phase differences between the different parts of the surface

Of these, the first three have simple relations between actuating force, frequency, and amplitude of motion, and would, therefore, appear to offer most promise of affording a sound source of constant efficiency. The resistance-controlled diaphragm, while difficult to obtain, is included in the list as representing a possible type and is of theoretical interest. It will be assumed in discussing the first three types of diaphragm that all parts of the surface move together, which means that either the diaphragm is small and rigid, or else the actuating force is applied to all parts. The wave action diaphragm is best represented by the large, shallow, paper cones which have been employed with considerable success. Familiar examples of this type are found in the Pathé and new Western Electric 540 AW loud speakers. Some other experiments along these lines were recently reported by Sutton.[8] Here the actuating force is applied at the center, or vertex, and flexural waves radiate toward the outer edge. If there is considerable energy loss so that these waves are attenuated rapidly, the net result is that at high frequencies a small area of the diaphragm near the vertex radiates sound, while at lower frequencies a larger area works. If the attenuation of the flexural waves is small, standing-wave conditions exist and there is a series of frequencies at which resonance occurs.

The relation between amplitude, frequency, and driving force, for diaphragms with pure elastic, resistance, or inertia control is as follows. If the diaphragm vibrates with simple harmonic motion at a frequency f cycles per second, and with an amplitude X centimeters, the deflection may be expressed by

$$x = X \sin 2 \pi f t = X \sin \omega t, \text{ centimeters} \quad (1)$$

the velocity is

$$u = \frac{dx}{dt} = \omega X \cos \omega t \text{—centimeters per second} \quad (2)$$

and the acceleration is

$$\alpha = \frac{du}{dt} = \frac{d^2 x}{dt^2} = -\omega^2 X \sin \omega t \quad (3)$$

centimeters per second, per second.

With elastic control, the deflection is proportional to the applied force; or to give the deflection shown in (1), we must apply a force

$$F \sin \omega t = K x = K X \sin \omega t \quad (4)$$

in which F = maximum force in dynes, and K the diaphragm stiffness in dynes per centimeter.

From (4)

$$X = \frac{F}{K} \quad (5)$$

or the amplitude is proportional to the maximum of the alternating force, independent of frequency.

With resistance control of motion the velocity is proportional to the instantaneous applied force, or to give the motion expressed in equation (2) we must apply a force

$$F \cos \omega t = R u = R \omega X \cos \omega t \quad (6)$$

in which R is the resistance to motion in dynes per unit velocity.

From (6)

$$X = \frac{F}{\omega R} = \frac{F}{2 \pi f R} \quad (7)$$

or the amplitude is proportional to the applied force divided by the frequency.

In the case of inertia control, the applied force is equal to the mass M times the acceleration. Hence to obtain the motion expressed in equations (1), (2) and (3) we must apply a force

$$-F \sin \omega t = M \alpha = -M \omega^2 X \sin \omega t \quad (8)$$

or

$$X = \frac{F}{\omega^2 M} = \frac{F}{4 \pi^2 f^2 M} \quad (9)$$

In this case the amplitude for a given driving force varies inversely as the square of the frequency.

There are two classes of diaphragms the sound radiation of which are simple functions of amplitude, frequency and diaphragm size.

a. Diaphragms large enough in comparison with the longest waves to give plane-wave radiation for all essential frequencies.

b. Diaphragms small enough in comparison with the shortest waves, to be treated as virtually point

8. *Wireless World and Radio Review*, Nov. 19, 1924.

sources for all essential frequencies, circulation of air between the front and back of the diaphragm being prevented by either a baffle or by enclosing the space on one side of the diaphragm.

The power in ergs per second[9], radiated from one side of the large diaphragm is

$$P = \frac{1}{2} \rho v S \omega^2 X^2 \qquad (10)$$

in which

ρ = mean density of air in grams per c. c.
v = velocity of sound in air in cms. per sec.
S = area of diaphragm in sq. cm.
$\omega = 2 \pi f$
X = amplitude of diaphragm motion, assumed to be the same over the entire surface.

In the case of the small diaphragm, the power radiated from one side is[10]

$$P = \rho \frac{S^2 \omega^4 X^2}{2 \beta v} \qquad (11)$$

in which β is the solid angle into which the radiation takes place, 4π for complete spherical waves, and 2π for hemispherical waves, or in other words, if a flat baffle is used. With a flat baffle, the radiation from both sides of the diaphragm is

$$P' = \rho \frac{S^2 \omega^4 X^2}{2 \pi v} \qquad (12)$$

For these two types of diaphragm we can see from equations (**10**) and (**12**) what would have to be the relation between amplitude and frequency in order to have the sound output the same at all frequencies.

For the large diaphragm, equation (**10**) shows that P becomes independent of ω or of f if X varies as $\frac{1}{f}$, and equation (**7**) shows that applying a force, F, the same at all frequencies to a resistance controlled diaphragm, gives an amplitude which varies as $\frac{1}{f}$. If we have the means for making the force F a direct or inverse function of frequency, a large diaphragm with inertia or elastic control can be made to give the same output at low and high frequencies. For example, in the polarized electrostatic sound source, the force variation is proportional to the alternating voltage between electrodes. If the charging current supplied to the electrodes is fed through a resistance high compared with the capacity reactance of the device, then a constant voltage applied to the resistance and capacity in series will result in a voltage across the capacity inversely proportional to the frequency, and such a voltage will give constant sound radiation from a large area elastic control diaphragm. In like manner in the case of magnetically actuated diaphragms, in which the force is in general proportional to the current, if the inductive reactance of the windings is high compared with their resistance plus the plate resistance of the amplifier tube, the current through the windings will be proportional to the voltage applied to the grid of the tube, divided by the frequency. This will give the desired relation between force and frequency, for constant sound radiation from a large area elastically controlled diaphragm.

If we extend the consideration to the use of pick-up devices or transmitters having direct or inverse frequency characteristics, or include compensating circuits of the type shown in Fig. 7, there are many combinations which give a constant over-all efficiency. Of such combinations, those which throughout the system preserve the normal balance between high and low frequencies, have the advantage that a satisfactory ratio of useful to stray noises is more readily maintained, and the required amplifier capacity is less. We shall, therefore, assume that the goal is to produce a sound source which, when operated by the output of an amplifier tube, will give a sound wave pressure proportional to the voltage applied to the grid of the tube, the proportionality factor being independent of frequency. Such a sound source is the large diaphragm electrostatic unit, with resistance controlled diaphragm motion, and with capacity reactance high compared with the tube plate resistance. Another example is the large diaphragm electrostatic unit with elastic control of the diaphragm and with capacity reactance low compared with the tube plate resistance throughout the essential frequency range. Electromagnetically driven large area diaphragms, with elastic control of motion and inductive control of curent, or with resistance control of motion and resistance control of current, are also possibilities.

Turning to the case of the small diaphragm working with a baffle, equation (**12**) shows that for constant sound output $X^2 \omega^4$ must be constant, or the amplitude must vary inversely as the square of the frequency, and equation (**9**) shows that a constant driving force and inertia controlled motion gives just this required relation between frequency and amplitude. This relationship was pointed out by Kellogg who took especial interest in this type of device and designed all of the models employing small rigid diaphragms. The driving force independent of frequency is available in the form of a coil in a constant magnetic field and with enough resistance in the circuit compared with the reactance to make the current independent of frequency. There are obviously other combinations using small diaphragms, such as resistance control of motion and inductive control of current, which would give constant output, but the inertia controlled small diaphragm with resistance controlled current has all the advantages.

9. Rayleigh, Theory of Sound. Vol. II. Page 16.
10. Rayleigh, Theory of Sound. Vol. II. Page 113.

Effect of Intermediate Diaphragm Size

Formulas for the sound radiation from a flat circular diaphragm situated in a flat wall or baffle of infinite extent have been developed by Rayleigh[11], all parts of the diaphragm being assumed to have the same motion. Fig. 10 shows the relative output at different frequencies of an inertia controlled diaphragm six inches in diameter, actuated by a vibratory force of variable frequency but constant magnitude. For wave lengths greater than about 1.5 feet, (46 cm.), the diaphragm may be treated as a small source, and the sound output is constant. At frequencies for which the wave length is less than the diameter of the diaphragm, the radiation practically follows the law expressed in equation (**4**) for large area diaphragms. Within this part of the frequency range inertia control gives too rapid a drop in amplitude as the frequency is increased, with the result that the power radiated is less at high frequency. There is, however, a compensating effect. At the same

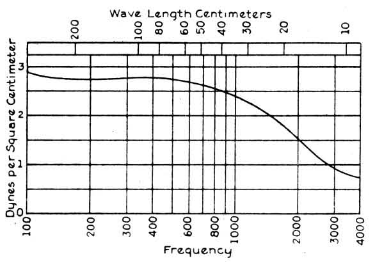


Fig. 10—Radiation Characteristics of Inertia Controlled Diaphragm Six In. (15 Cm.) in Diameter

Ordinates are R. m. s. Pressure at One Meter Distance

$$= \sqrt{\rho v \times \frac{\text{Power radiated from one side}}{\text{Area of hemisphere of 100 cm. radius}}}$$

In which

ρ = Density of Air
= 0.0012 grams per cu. cm.
v = Velocity of Sound
= 3.42×10^4 cm. per sec.
Actuating force assumed = 83,000 dynes. r. m. s. value
Mass = 10 grams

time that the total radiation becomes less, the directivity increases, and the listener in front of the diaphragm receives a larger share of the total power radiated. The result is that with a diaphragm of this size, the listener, if stationed in front of the diaphragm, loses very little of the high frequency components. Even with larger diaphragms, very pleasing results have been obtained with inertia-controlled diaphragms, notably the Hewlett induction phone in which a 24-in. diaphragm has been employed with good effect. In this the tendency to give excessive radiation of low tones is reduced by the fact that no baffle is employed, and there is a diminution in diaphragm currents at low frequency due to imperfect transformer action. The directive properties of this large area diaphragm are very striking.

In order to radiate in accordance with equation (**12**) or as a small source, up to 5000 cycles, a diaphragm would have to be less than about 1 ½ inches in diameter, but since experiments indicate that much larger inertia-controlled diaphragms give good results, there is no justification for limiting the size to the value mentioned, particularly as sensitivity is gained from the adoption of larger sizes.

Requirements for True Piston Action

Since the inertia-controlled small diaphragm appeared, from both theoretical and experimental evidence, to offer the greatest promise of a practical solution of the loud speaker problem, subsequent experiments were devoted to finding the best form of device embodying this principle. The first models left much to be desired in the way of sensitivity and considerable room for improvement in quality. The condition that the diaphragm must move as a unit meant two alternatives; either the diaphragm must be very rigid for its weight and must be quite small, or the driving force must be applied uniformly over the entire diaphragm surface.

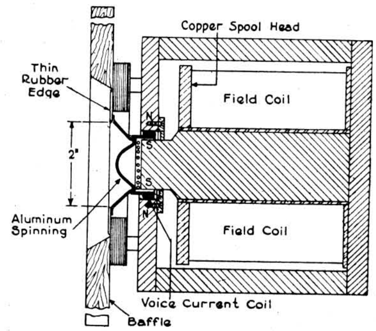


Fig. 11—Baffle-Type Rigid Diaphragm, Loud Speaker

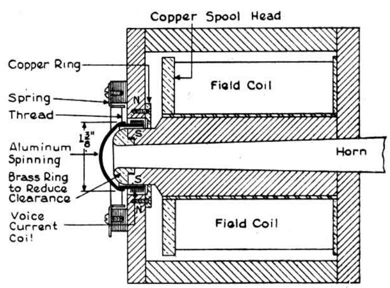


Fig. 12—Rigid-Type Diaphragm Adapted for Use with a Horn

Models with Rigid Diaphragms

Two of the most satisfactory forms of small rigid diaphragms are shown in Figs. 11 and 12. Of available materials, aluminum has as high a ratio of elastic modulus to density as any, combined with light weight. The oil seal of Fig. 4 was considered impractical for any but a laboratory model, and in place of it, either small clearance was depended upon to prevent leakage or a thin rubber membrane was used to bridge the gap between moving and stationary parts. Fig. 12 was de-

11. Theory of Sound. Vol. II. Pages 162-165.

signed for use with a horn[12]. The horn was four and one-half feet long with an exponential expansion from ½ inch to 30 inches diameter. Fig. 13 shows the same horn with the earlier model instrument illustrated in Fig. 9. Such a horn carries down to about 200 cycles satisfactorily and has no very strong resonances[13].

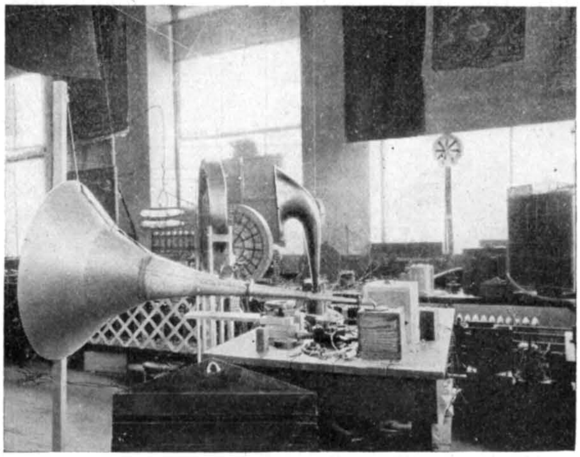


Fig. 13—Rigid-Type Inertia-Controlled Diaphragm with Exponential Horn

Resistance and not inertia control is the ideal diaphragm characteristic for an instrument employing a slow expanding exponential horn, and that pleasing results should be obtained with the free diaphragm must be ascribed to the fact that the diaphragm never attained the amplitudes at low frequencies corresponding to true inertia control, because of damping by the air column in the horn and strong electromagnetic damping characteristic of the moving coil drive. A

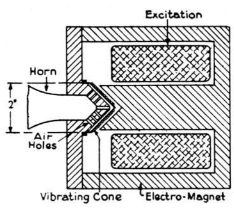


Fig. 14—Commercial Gaumont Loud Speaker

horn of adequate dimensions, however, is exceedingly bulky, and better results were subsequently obtained with flat baffles.

Models with Distributed Driving Force

Of the devices in which the actuating force can be applied over the whole diaphragm area, thus making rigidity unnecessary, the electrostatic phone and the Hewlett induction phone have already been mentioned. In the latter, the air-gap length is the radius of the diaphragm, and a very strong magnetic field is practically out of the question. As a result the efficiency is low and the fine quality of which the instrument is capable is secured at the cost of a high power amplifier and considerable direct-current power for excitation. It is, therefore, not a household device, its field of application being rather in auditoriums.

Rice urged the probable value for the case of the small diaphragm instruments, of distributing the driving

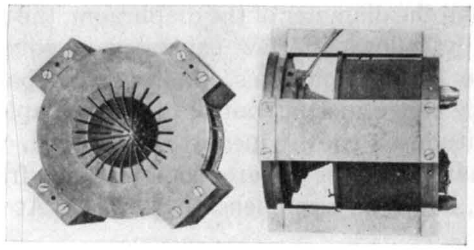


Fig. 15—Gaumont Type Loud Speaker Assembled

force over the entire diaphragm area, and believed that this could be done without sacrifice of field flux density. At this juncture a letter was received from Dr. W. R. Whitney describing a loud speaker which had been shown him in France by its inventor, Mr. Gaumont, and which fulfilled this condition.

Fig. 14 shows the construction of the commercial loud-speaker built by the Société des Etablissements Gaumont. The diaphragm is a cone of thin silk, to

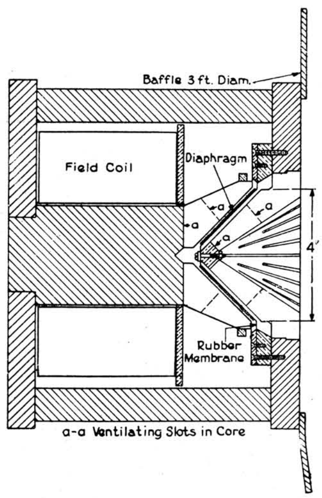


Fig. 16—Modified Design of Gaumont Type Loud Speaker

which is cemented a single layer spiral of fine aluminum wire. An extremely light diaphragm is thus possible, making for sensitiveness and freedom from resonance. The reaction of the voice currents in the aluminum coil with the radial component of the magnetic field gives the useful driving force.

Figs. 15 and 16 show one of the Gaumont type loud speakers designed by Rice, for use with a baffle. The

12. A description is given in the *Wireless World* and *Radio Review* of Dec. 17, 1924, by Capt. H. T. Round, of a loud speaker resembling that shown in Fig. 12 in some respects.

13. "Function and Design of Horns for Loud Speakers" by C. R. Hanna and J. Slepian, Jour. A. I. E. E., March, 1924.

"The Performance and Theory of Loud Speaker Horns" by A. N. Goldsmith and J. P. Minton, *Proc.* I. R. E., Aug. 1924.

diaphragm support used in the commercial instrument shown in Fig. 14 does not afford sufficient flexibility. The substitution of a flat edge of thin rubber, as illustrated in Fig. 15, gave the necessary flexibility without which adequate radiation of low tones from a small diaphragm had been found impossible. Experiments also indicated that a considerably heavier diaphragm

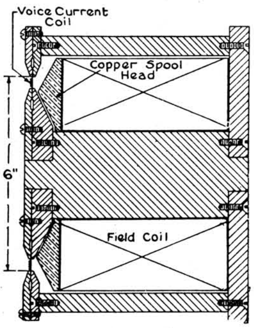


Fig. 17—Construction of Annular Type Loud Speaker

than that employed in the commercial machine was required for good balance between high and low frequencies. The diaphragm which worked best was four inches in diameter and weighed 11 grams. It consisted of a single layer of copper wire embedded in rubber,

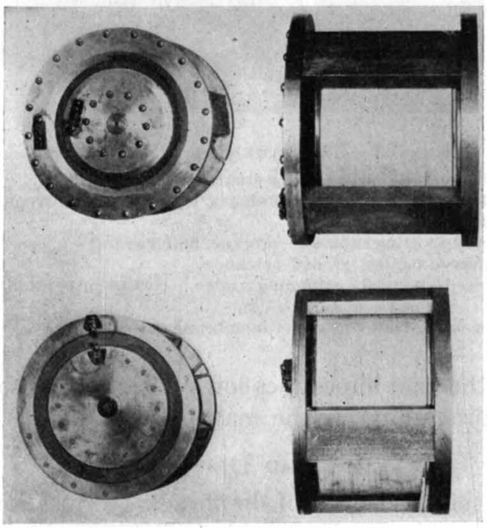


Fig. 18—Views of Two Annular Type Instruments

which gave a soft, non-resonant structure. Adequate venting proved to be of utmost importance in this design in order that air reactions on the diaphragm might not affect its motion adversely and in order to let out the sound without muffling. A baffle 3 ft. in diameter was employed.

An annular diaphragm type of loud speaker having uniformly distributed driving force is shown in Figs.17, 18 and 19. This instrument which was designed by Rice presents no venting difficulties and gives the possibility of considerable diaphragm area. A thin rubber membrane spans the air-gap, and a single layer coil cemented to the membrane provides the driving force. The construction difficulties are much less and the total weight less than in the case of the conical diaphragm type. In the annular design, if the air-gap is kept short enough to give reasonable magnetic field strength, it becomes difficult to make the natural frequency of the diaphragm low enough to fall below the important acoustic range. Electrical correction by

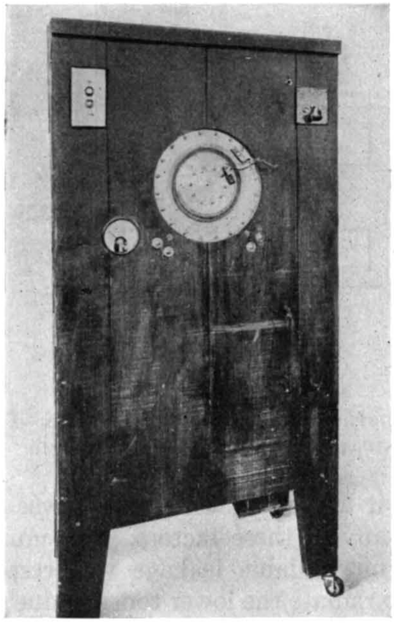


Fig. 19—Annular Type Loud Speaker Assembled in Cabinet with Amplifier

means of a series-tuned shunt across the output of the amplifier eliminated the most objectionable results of the diaphragm resonance, and in this form the device was very satisfactory. A somewhat similar instrument used as a transmitter has recently been described by Round[14].

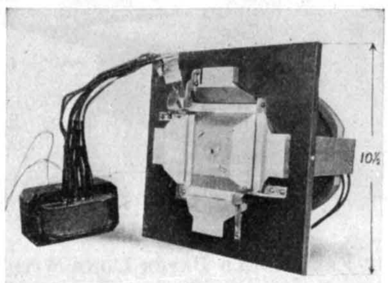


Fig. 20—Aluminum Foil Diaphragm Loud Speaker with Transformer

Efforts to gain sensitivity by the use of extremely light diaphragms have always, in our experience, led to disappointment. The expected gain in sensitivity was not realized, and in most cases the light diaphragm devices were very high pitched; or in other words,

14. *Wireless World and Radio Review*, Nov. 26, 1924.

radiated too much high frequency sound compared with the low. This, for example, was the characteristic of the design shown in Fig. 20 in which a strip of aluminum foil[15] a half mil thick, by a half inch wide, carrying the voice current and vibrating in a gap between magnet poles served as diaphragm. Careful transformer design, very flexible mounting of the foil, and an adequate

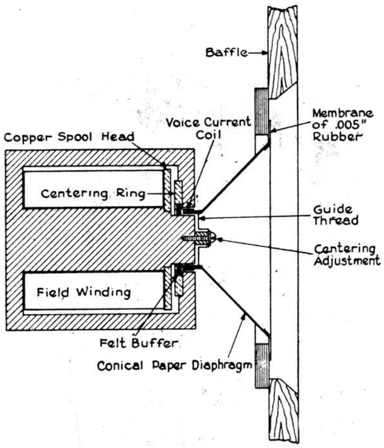


FIG. 21—CONSTRUCTION OF FREE EDGED, COIL-DRIVEN, CONICAL DIAPHRAGM LOUD SPEAKER

baffle made it appear that the result was not due to overlooking any of these factors. We must conclude either that unavoidable leakage was responsible for the failure to radiate the lower tones in due proportion,

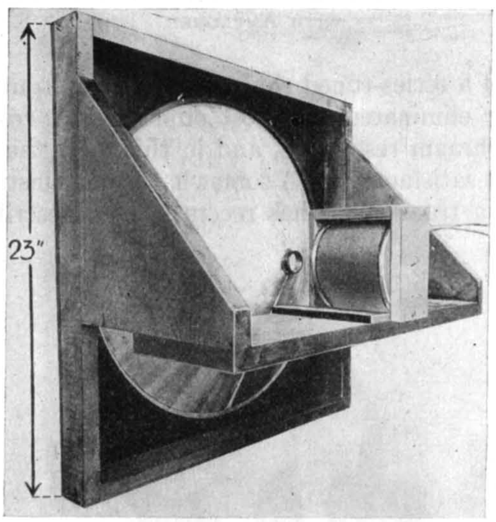


FIG. 22—LARGE FREE-EDGED PAPER CONE WITH COIL DRIVE

or else that air reactions, and electromagnetic damping play such important parts in the diaphragm motion compared with the inertia of the diaphragm itself, that the motion cannot be looked upon as inertia controlled, except in the upper frequency range.

Electromagnetic damping by the reaction of the driving coil with the magnetic field takes the form of a counter electromotive force which reduces the supplied current and driving force. The net result is the same as though the driving force had remained constant and a retarding force had been developed by a counter current generated by the motion of the coil. Thus "motional impedance" and electromagnetic damping are two aspects of the motion of the conductor in a magnetic field. Electromagnetic damping only becomes an important factor when the motional impedance becomes considerable compared with the other resistances and reactances in the circuit. Electromagnetic damping can be controlled in a measure by the ratio of transformation if a transformer is used. Making the load impedance high compared with the tube plate resistance gives maximum damping, while

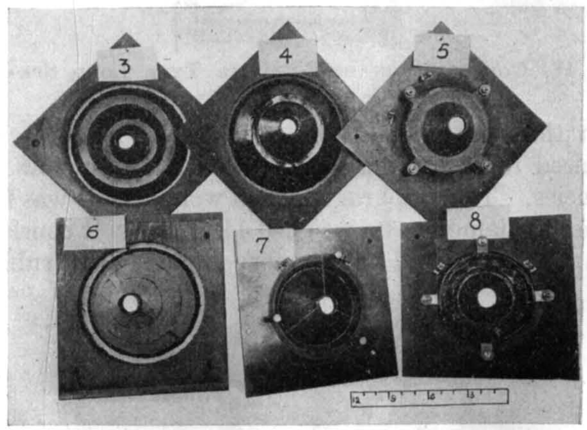


FIG. 23—EXPERIMENTAL DIAPHRAGMS

3. Mechanical filter type, three stages
4. Mechanical filter type, two stages, center for high frequency, whole surface for low
5. Extra supporting rubber membrane, half way out
6. Reinforced center, graded thickness
7. Reversed conical stiffening edge, thread-suspension, no-edge membrane
8. Extra supporting, flat-paper membrane half-way out.

making the load impedance low relative to resistance in the circuit minimizes the magnetic damping.

SEMI-RIGID DIAPHRAGMS

With the rigid type of diaphragm, a question to be settled experimentally was how large could the diaphragm be made before the quality of sound reproduction became impaired through failure of the diaphragm to act as a unit or plunger throughout the entire frequency range. A simple cone is an exceedingly rigid structure for its weight, particularly with respect to vibrations of the type which could be excited by a symmetrically applied force in the axial direction, such as is used in driving a conical diaphragm; or in other words, the cone is rigid with respect to vibrations like the opening and closing of an umbrella. With an angle of 45 deg. between the axis and wall of the cone, the rigidity is practically at its maximum. Paper cones of various sizes were tried with free or flexibly supported outer edges, using baffles to prevent circulation and

15. A loud speaker employing an aluminum strip in a magnetic field, manufactured by Siemens & Halske is described in "The *Wireless World* and *Radio Review*," July 2, 1924.

small coils as shown in Fig. 21 for drive. Diameters from 4 to 24 in. and angles from 45 deg. to 75 deg. were tried. These paper cones gave marked increase in

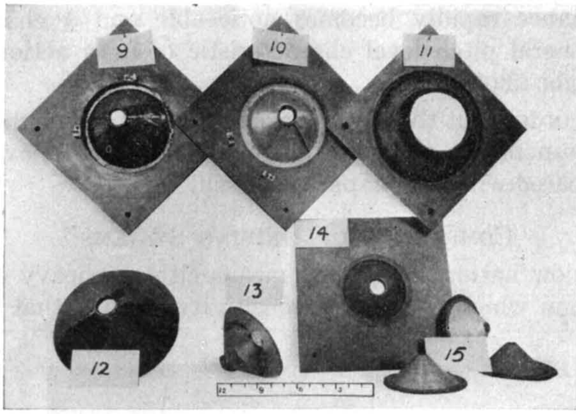


FIG. 24—EXPERIMENTAL DIAPHRAGMS

9. Glacine-paper cone 0.0015 in. thick, flat edge of same material
10. Aluminum Cone 0.002 in. thick, 0.005 in. rubber edge
11. Large coil, 4½ in. diameter, three-ply cone, 0.18 in. blotting Paper between Sheets of half-tone paper
12. Blotting paper, surface hardened with shellac to increase rigidity
13. Internal conical stiffener
14. Rubberized cloth, same material for edge
15. Early experiments with coil-driven cones four in. diameter bond paper, blotting paper and 0.010 in. aluminum

sensitivity over the devices shown in Figs. 11, 12, 15 and 17, the general sensitivity on speech being at least equal to that of a good horn type loud speaker. Size seemed

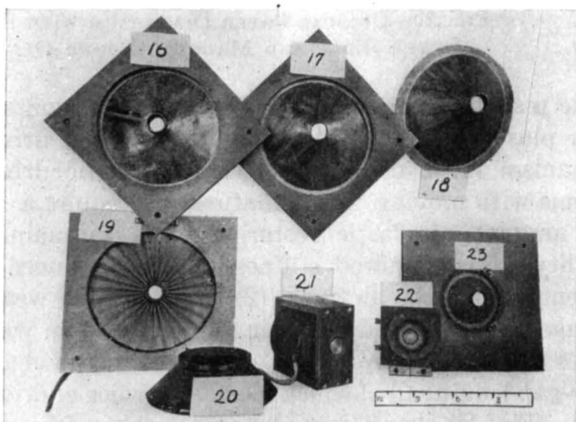


FIG. 25—EXPERIMENTAL DIAPHRAGMS

16. Eight-in. diameter cone, one in. deep to vertex, 0.007-in. paper, rubber edge 0.005 in. thick and ¼-in. wide
17. Same as (16) except two in. deep to vertex
18. Eight-in. diameter, 45-deg. cone, 0.007-in. paper, ¼-in. rubber edge
19. Lumier type diaphragm rocker joint at center, coil-drive, outer edge damped with sponge rubber
20. 4½-in. diameter coil, aluminum wire, cone eight in. diameter, 45 deg. of 0.007 in. paper
21. Field magnet for coil drive.
22. Aluminum spinning diaphragm with rubber edge for coil drive
23. 3¾ in. diameter 45 deg. cone. 0.007 in. paper; flat paper edge 0.0035 in. thick by $^3/_8$ in. wide.

to have little effect on general sensitivity, but did somewhat alter the quality, diameters between four and eight inches giving the best results. The angle did not appear to be critical, but with very shallow cones speech sounded muffled, the high frequencies being lacking.

A rough calculation indicates that a 45 deg. paper cone 4 in. in diameter would begin to depart materially from rigid plunger action, at frequencies of between 3000 and 4000, while with larger diameter cones the change would take place at lower frequencies. The paper-cone diaphragms used in this series of tests must, therefore, be considered as acting substantially as

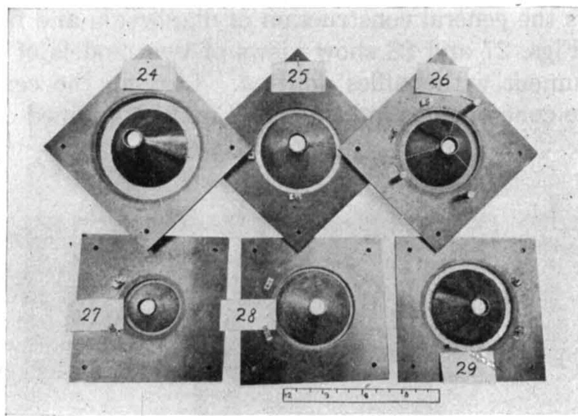


FIG. 26—EXPERIMENTAL DIAPHRAGMS

24. 5¾ in. diameter 45 deg. cone of 0.007 in. paper with one in. flat paper edge
25. Same as (24) with $^3/_8$ in. wide paper edge
26. 5¼ in. diameter 45 deg. cone of 0.007 in. paper with 0.005 in. rubber edge ½ in. wide. Guide threads to center coil
27. 3¼ in. diameter 45 deg. cone of 0.007 in. paper with ¼ in. wide rubber edge
28. 5¾ in. diameter 45 deg. cone of 0.007 in. paper with 0.005 in. rubber edge ¼ in. wide
29. Same as (28) except ½ in. wide silk edge

plungers for the lower frequencies with a gradual transition to wave action or progressive deflection at the higher frequencies. If there was any loss of quality due to the failure of the diaphragm to move as a whole at high frequencies, there was a compensating improvement as compared with the small diaphragm instruments, in a better radiation of the low tones, for the small diaphragms did not give

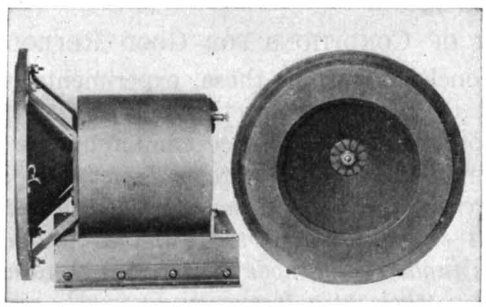


FIG. 27—FREE-EDGED, COIL-DRIVEN, CONICAL PAPER DIAPHRAGM LOUD SPEAKER UNIT

quite enough low frequency radiation. An extended series of tests was made to see whether a further improvement in quality could be obtained, making the cone of various materials and different thicknesses and by employing stiffening members to reduce the tendency of the cone to break up into vibrations either of the kind with circular nodes or with radial nodes. Figs. 22 to 26 inclusive show some of the forms of diaphragm tried. Nothing better was found, however, than a simple 45-deg. cone of 0.007-in. to 0.010-in. paper, about six in. in diameter, with a flexible support around the outer edge consisting of a membrane of rubber 0.005 in. thick and ¼ in. wide, under very slight tension. Fig. 21 shows the general construction of diaphragm and field, and Figs. 27 and 28 show views of two models of the instrument with baffles omitted. Leaving the center of the cone open as indicated in Fig. 21 simplified construction and avoided the necessity of venting the space in front of the magnet core. A baffle, two feet square, appeared adequate. If the shortest air path between the front and back of the diaphragm is a quarter wave length or more there is no loss of radiation through circulation, although regions of interference between the two sound sources appear. An eight-foot wave length corresponds to a frequency of 135 cycles, and loss of output below this frequency may be attributed, in part, to circulation.

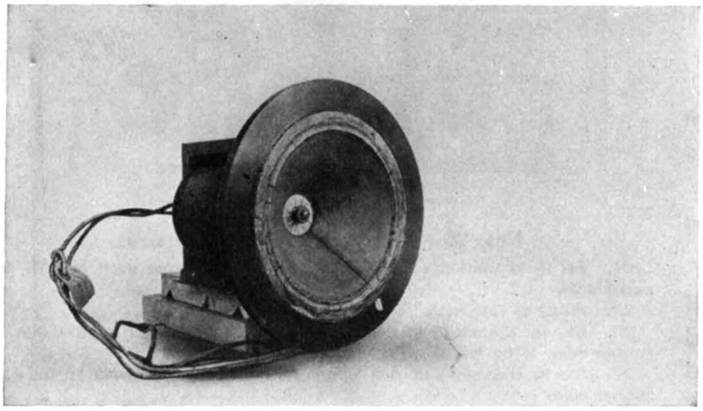


Fig. 28—Coil Driven Conical Paper Diaphragm, Loud Speaker Unit with Flexible Paper Edge

Summary of Conditions for Good Reproduction

The conclusion from these experiments was to the effect that the best practical solution of the loud speaker problem was a device combining the following features: *a conical diaphragm four inches or more in diameter with a baffle of the order of two feet square to prevent circulation and so supported and actuated that at its fundamental mode of vibration the diaphragm moves as a whole at a frequency preferably well below 100 cycles.*

The larger the diaphragm the less seriously will the baffle be missed if omitted. Thus, if the diaphragm were two feet in diameter, the effect of adding a baffle would be difficult to detect by ear. The use of the baffle gives latitude in the choice of diaphragm size. The baffle need not necessarily be flat, but if concave the solid angle included on the concave side should be at least as great as that in a cone with an angle of 45 deg. between wall and axis. With a smaller solid angle, resonance rapidly becomes noticeable and a change in general pitch level characteristic of horn action is brought about[16].

In order that the diaphragm may vibrate as a whole, the support at the outer edge must be very flexible compared with the diaphragm itself.

Comparison of Driving Systems

A low natural frequency means either a heavy diaphragm which would cost sensitivity, or else that the elastic restoring force supplied by the diaphragm supports plus any elastic restoring force in the driving mechanism must be small. Electromagnetic driving systems with moving iron armatures all require a certain amount of elastic restoring force to maintain stability. The required stiffness may be reduced by (1) lengthening the air-gaps, (2) working with weaker average magnetic field, (3) using a lever system which makes the diaphragm motion greater than the change in air-gap length; all of which mean a sacrifice of driving force. Fig. 29 shows a model employing a free edge cone with iron armature drive. By using a fairly large diaphragm and working close to the limit of stability it is possible to use this type of drive and obtain a low enough natural frequency and moderate sensitivity, but the moving coil drive has the following advantages: 1. The elastic restoring force may be made as low as desired without sacrifice of sensitivity. 2. Very large amplitudes can be allowed. (With a drive using variable length air-gaps, the change in gap length must always be small compared with the average length if distortion is to be avoided). 3. The relation between current and force is strictly linear and there-

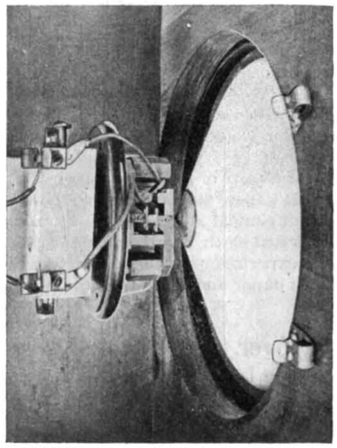


Fig. 29—Conical Paper Diaphragm with Free Outer Edge and Magneto Phone Drive

16. "Effect of a Horn on the Pitch of a Loud Speaking Telephone," by E. W. Kellogg, *General Electric Review*, August, 1924.

fore distortion due to bends in the magnetization curves of iron is avoided in the moving coil drive. 4. If a strong magnetic field is provided the coil drive gives greater sensitivity than the iron armature drive. 5. No adjustment is upset if the weight of the diaphragm causes it to shift somewhat when the instrument is tilted. The disadvantages of the moving coil drive are the size and weight of the field magnet and the power required for excitation, but these disadvantages are outweighed by the advantages, in the opinion of the writers and their associates, particularly, when a special amplifier is part of the loud speaker equipment. A loud speaker with moving coil drive and permanent magnet field is shown in Fig. 30.

Fig. 30—Moving Coil Type Loud Speaker Unit with Permanent Magnet Field and Three-Pass Exponential Horn

Comparison of Free and Fixed Edge Cones

It may be of interest to compare the action of the flexibly supported conical diaphragm with that of one with comparatively rigid support. The latter has had extensive application in hornless loud speakers. If a vibrating force of constant strength, but variable frequency is applied at the vertex of the rigidly supported cone, there is small motion and little sound radiation at frequencies below the lowest resonance. Additional resonances occur at frequencies of the order of 3, 5, 7 times that of the fundamental. In order that low tones shall not be almost entirely lost in the output of such a device, it must be constructed so that the fundamental resonance occurs at a frequency low in the range of important sound. The diaphragm action may be said to be characterized by a series of resonances. The upper resonances are closer together on the musical scale, and this together with the greater damping makes the radiation more nearly uniform in this part of the range. The very high frequencies, however, are not adequately radiated when the cone is made very flat, or shallow compared with its diameter. The requirement of a low fundamental resonance calls for a shallow cone, unless the diameter is very large. The choice of angle is, therefore, a compromise.

The free-edged cone permits large amplitudes at low frequency, and as already pointed out the relation of amplitude to frequency is such as to maintain practically constant radiation. Since the radiation of the lower frequencies is not critical to either size or cone angle, these factors may be chosen entirely with reference to obtaining the best effects at high frequencies. Since the flexural waves which travel from the vertex toward the edge, are reflected as well by a free as by a fixed edge, only in opposite phase, standing wave conditions with circular nodes can occur with the free edge cone as well as with one having a fixed edge, and hence a series of resonances is possible. If the cone is steep, which means high velocity wave propagation, and small in diameter, the first resonance will occur at a high frequency, and the action characterized by a series of resonances will be confined to a minor part of the essential frequency range. Strong resonances in this region have not been observed, from which fact the conclusion must be drawn that damping in the diaphragm material and perhaps also in the material of the flexible edge is considerable.

The difference in the action of the diaphragms may be illustrated by the analogy of the behavior of two electrical transmission lines when an alternating voltage of variable frequency is applied. The free edged diaphragm is like a line short circuited at the end farthest from the generator, and the fixed edge diaphragm corresponds to an open circuited line. Current in the line is analagous to velocity of motion of the diaphragm. Large currents can be sent through the short-circuited line at low frequencies, the voltage and line inductance determining the current values. No resonance occurs until the frequency reaches a value which makes the line a half wave length long. Additional resonances occur at frequencies two, three, four, five, or more times that of the first. In the case of the open-circuited line little current flows until the first resonance is approached, at which the line is a quarter wave length long. The higher resonances are at frequencies three, five, and all odd multiples of the first. To make the fundamental resonance occur at a low frequency, the line must be long, and constructed in such a way that the rate of wave propagation is slow.

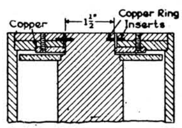


Fig. 31—Copper Ring Inserts to Reduce Impedance of Moving Coil

Copper Rings to Reduce Impedance

In loud speakers employing a moving coil drive the radiation at high frequency can be increased, if desired, by a scheme due to Rice which consists in placing copper rings near the moving coil, so disposed that they form short-circuited secondaries and reduce the impedance of the coil at high frequency. In one coil tested the impedance at 4000 cycles was 57 ohms without the copper rings and 24 ohms with the rings in place. At 500 cycles the ohmic resistance of the coil was the principal factor, so that the rings had little effect. Fig. 31 shows the disposition of rings used for this purpose.

Special Amplifier

As was pointed out by Martin and Fletcher[17], voices and music do not sound natural unless reproduced at approximately the original level of intensity, even though the reproduction may be free from all wave form distortion. In order, therefore, that the full benefit of a high grade loud speaker may be realized, it is important that the amplifier which goes with it should have sufficient capacity to give a natural volume or intensity.

Fig. 32 shows the circuits of an amplifier which has proved satisfactory for household service. Two U V-216 kenetrons rectify 70 milliamperes at 550 volts. The field of the loud speaker serves as filter choke. In order that pulsations in the rectified current in the exciting coil may not cause changes in the air-gap flux and thereby produce hum and modulation of the sound output, the head of the spool on which the field coil is

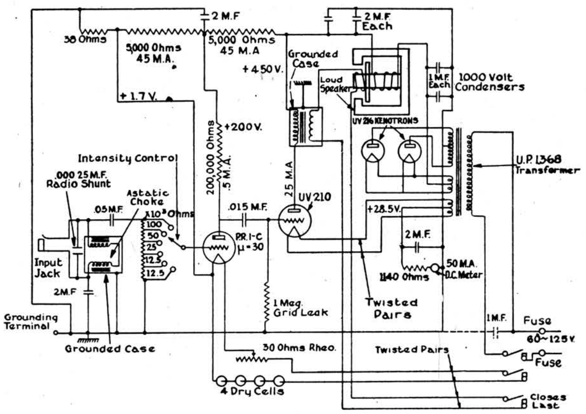


Fig. 32—Rectifier and Amplifier Circuit

wound is made of copper one-fourth inch thick. This expedient suggested by Kellogg steadies the flux so that there is almost no ripple. About 100 volts are dropped in the field coil, leaving 450 volts for the plate supply of the U V-210 radiotron which serves as the power tube. A bias of about 28 volts is required for the grid, and this bias is obtained by dropping 28 volts in a resistance so that the filament runs at a mean potential of + 28 volts with respect to the negative terminal of the rectifier. This makes the net plate voltage across the tube about 422, and the mean plate current is 25 milliamperes. Under these conditions an average U V-210 radiotron can send 10 milliamperes, r. m. s. value, of sine wave current through a 10,000 ohm load without appreciable wave distortion[18]. This represents about thirty times as much power as the same tube could put out with a plate supply of 120 volts.

Cabinet Set

Figs. 33 and 34 are views of a laboratory model of a cabinet set containing rectifier, amplifier and loud speaker. The front of the cabinet acts as baffle. To prevent air resonance in the box, the sides and back are vented by inserting panels of perforated brass. The ammeter shown in the picture is connected to read the plate current of the radiotron. Whenever the peak

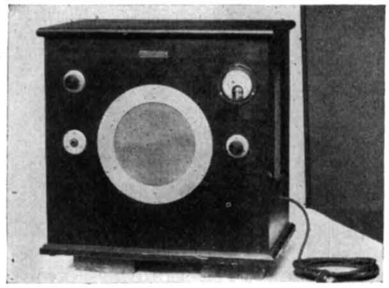


Fig. 33—Laboratory Model of Cabinet Set—Front View

values of the voltage applied to the grid of the tube exceed the value for which distortionless operation is possible the meter needle shows disturbance. If roughness commonly termed "blasting" is noticed in the reproduction, and if at the same time the meter needle kicks, the intensity of the input should be reduced. If the meter needle is steady, the fault is probably not in the amplifier.

Psychological Factors

Certain experiences connected with testing and demonstrating loud speakers of the type we have de-

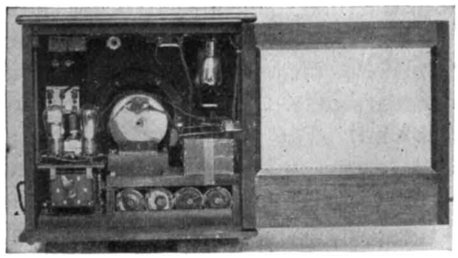


Fig. 34—Laboratory Model of Cabinet Set—Back View

scribed are of interest. The possession of an instrument in which distortion is minimized and whose response covers a wide frequency range, transfers the interest of the broadcast listener from "fishing" for distant stations to that of trying to find the best program among the near-by high grade broadcasting stations, and to enjoying the music or speeches themselves.

17. "High Quality Transmission in Reproduction of Speech and Music," by W. H. Martin and H. Fletcher. Journ. A. I. E. E., March, 1924.

"Physical Measurements of Audilion and their Bearings on the Theory of Hearing," by H. Fletcher. *Jour.* Franklin Inst., Sept., 1923.

18. Design of Distortionless Power Amplifiers, by E. W. Kellogg, A. I. E. E., 1925 Midwinter convention.

There are, on the other hand, conditions when the difference between the loud speaker with a wide frequency range, and one of the ordinary horn type which loses both very high and low frequencies, is not at all striking, and the latter may even sometimes be preferred. Measurements of sound intensity required for audibility[19] show that as intensity is reduced, the low tones will be lost first, since the threshold intensity for example of a 100-cycle tone is of the order of fifty times that for a 1000-cycle tone, intensity being expressed in sound wave pressure. As a result of this, when the reproduction as a whole is very faint, the instrument which produces the low tones does not sound materially different from one which does not, for even if reproduced in the correct relative intensity compared with the higher tones, the low tones are below audibility.

When a radio program is half smothered in static, it may sound better through a loud speaker whose response is mainly between 500 and 2000 cycles, than through one having a greater range. The energy in the incoming static is likely to be almost uniformly distributed over the audio frequency range, provided the receiving set is not responsible for distortion, whereas the range 500 to 2000 cycles includes the major part of the essential voice frequencies. Extending the range above and below would add to clearness and naturalness in the absence of interference, but with heavy static it may often bring in enough additional disturbance to more than offset the gain. Lack of clearness may be less irritating to the listener than disturbing noises. Hence the enjoyment of the wide range loud speaker is largely confined to strong stations or else to times of comparative freedom from static. A similar observation applies to roughness caused by "blasting" from overworked amplifiers or other causes. When any piece of acoustic apparatus is worked beyond the maximum amplitude for which the output bears a linear relation to the input, the resulting wave distortion takes the form of the production of overtones. The rough harsh sounds which result are much less noticeable with an instrument which cuts off the high frequencies. Therefore, if the improved articulation and greater detail in music, which are made possible by response to high frequencies, are to be a real advantage, we must avoid the faults just mentioned in the currents supplied to the loud speaker. The logical place to begin is the amplifier associated with the loud speaker. This must be carefully designed and have ample capacity so that there will be little temptation to overwork it. Few pieces of apparatus are so frequently worked beyond their proper capacity as loud speaker amplifiers. This is natural in view of the initial expense of an adequate amplifier, and the desire for volume of sound from the loud speaker. With the usual type of loud speaker a slight overworking of the amplifier is hardly noticed, and rather than provide greater amplifier power, users of loud speakers have compromised with low volume and some amplifier distortion, and either educated their ears to accept the result as good, or else lost interest.

Another factor bears on the question of amplifier capacity. With distortion such as is usual in receiving sets and loud speakers the reproduction sounds best when weak, perhaps because the distortion is similar in some respects to the effects of distance. Use of such equipment results in one's forming the habit of enjoying faint music. With more nearly correct reproduction of the original music, enjoyment is increased by bringing the volume up to normal or the intensity to which one is accustomed when listening directly. In several instances it has been observed that when a loud speaker of the new type has been placed in the home of some one previously accustomed to a loud speaker of the usual construction, at first the listener preferred to keep the intensity very low, but after a few days we find him working with normal volume.

Output Measurements

Sound pressure measurements with constant input and variable frequency have been taken with two samples of the new type loud speaker, and these in general confirm the aural impressions that the instrument covers a wide frequency range without the great inequalities in output at different frequencies which characterizes loud speakers in general. Such measurements, however, are likely to be misleading unless extreme precautions are taken to avoid certain errors. Up to the time of writing the authors have not been able to obtain measurements under conditions with which they were completely satisfied, and it is, therefore, deemed best not to publish any of the output data so far obtained.

Acknowledgments

The writers wish to express their deep appreciation for the never failing interest and encouragement given by Dr. W. R. Whitney throughout the long investigation. We are also greatly indebted to our colleague, Dr. C. W. Hewlett, for many helpful suggestions and for the production of our first really high-grade loud speaker which was constantly used as a standard of comparison. We are further indebted to Mr. E. P. Lawsing for able assistance in the experimental work and to Mr. W. F. Winter in the mechanical construction.

Discussion

H. A. Frederick: In reading this paper one cannot but wish that some definite standard or method of rating might have been employed, so that the results of this investigation of many types of loud speakers might be placed quantitatively in definite positions on some scale of merit. Since the authors, as pointed out in the paper, have not as yet been able to obtain satisfactory quantitative measurements with their best designs, the readers are not in a position to judge the accomplishment.

19. Physical Measurements of Audition and their Bearing on the Theory of Hearing, by H. Fletcher, *Journ.* Franklin nst., e t. 1923, Bell System *Tech Jour.* Oct. 1923.

While these measurements are not simple and are liable to be misleading, unless very carefully made, still the same comment applies to qualitative judgments by the ear alone.

In this work, the authors have primarily stressed the obtaining of a loud speaker giving high quality; that is, one which faithfully and without distortion reproduces the sound whose electrical counterpart has been fed to it. In striving for this result, it is difficult also to obtain efficiency. In the authors' analysis of the problem they have largely sacrificed considerations of efficiency. For example, the "inertia control" used in their design involves a diaphragm 90 deg. out of phase with its driving force or, in other words, low power factor. They have also neglected motional reactions of the mechanical system on the electrical as well as transition losses due to the connection of vibratory systems of different impedances. The analysis as a result is limited in its field of application. It is probable, on the other hand, that improvements to overcome such losses will be effected and that they will make possible loud speakers of high quality which will also be of materially higher efficiency than those now available.

Another phase of the loud-speaker problem which would seem to warrant consideration is the load capacity. This, of course, must be defined in terms of sound-power output. A loud speaker, to be satisfactory for certain very important classes of service, must be capable of giving out a very considerable amount of sound without having the relation between output and input depart from a linear characteristic. In rating the various types studied it would be of interest to know how they were found to compare on this score; also, it would be of interest to know what were the limits of output found for these most promising designs and whether magnetic or vibratory, namely, mechanical limitations were first encountered or whether heating of the coil limited its output.

In the favored design, the size of the baffle, of course, sets a lower frequency limit while the size of the cone and its rigidity set a higher frequency limit. It would be of interest to know where these two limiting frequencies were to be found.

Near the end of the paper, it is stated that the stiffness of a magnetic-type motor system can be decreased by weakening the polarizing magnetic system. As pointed out by Hanna[1], the polarizing field gives rise to what might be termed a negative stiffness since it acts in opposition to the mechanical stiffness of the system and, therefore, has the opposite effect to that stated.

The authors state that "if a strong magnetic field is provided, the coil drive gives greater sensitivity than the iron-armature drive." I would like to ask if they would explain a little more in detail just what is meant by sensitivity, and how this conclusion was reached. It would seem that the magnitude of the mechanical force and the mass, as well as the electrical impedance and current, would have to enter a satisfactory expression for sensitivity.

In the article appears the statement that "four times the power is radiated with the baffle as with the back enclosed." Is the conclusion based on theoretical grounds or was it determined entirely by observation?

The reference to the resistance-controlled type as being of only "theoretical interest" might perhaps appear to underestimate its importance since any loud speaker to have high efficiency must be largely resistance-controlled, the resistance coming from useful radiation of sound into the air.

B. F. McNamee: The loud speakers which have been on the market using a movable coil system are supplied (as I suppose this one is) with a field current, usually from a storage battery. I believe that such loud speakers have met with a certain amount of sales resistance, due to that fact. Especially where dry-cell tubes are popular, a source of field current is not very readily available. I would like to ask how permanent field magnets would work out in this case, or what other provision has been made.

V. E. Thelin: In endeavoring to get quality of tone, I have adapted a Western Electric unit to a talking machine which has a wooden tone arm, as well as a wooden horn, and I attribute the fact that the so-called horn effect had disappeared to a considerable extent, to this wooden construction. I compared this combination with a new speaker of the parchment-cone type, and an adaptor type unit of another manufacture. I noticed that the Western Electric unit and the parchment type speaker gave the same volume and tone quality and it was difficult to tell them apart when they were operating at the same time. The adaptor type, however, changed the quality considerably and on the low notes of the piano it was very mushy.

It seems to me that there is a large field for the amplifier unit demonstrated here today. With a unit of this kind, it, no doubt, would be possible to take a phonograph record, and using a needle which has practically no scratching, and, therefore, has perfect tone, but whose music is too soft to be heard in the horn of the talking machine, and amplify it to a considerable volume but still retain the perfect tone quality. In this way it would be possible to preserve the music of the present-day artists on the radio and hear this music many years to come.

I would like to ask Mr. Kellogg if the baffle need be of a certain kind of material for obtaining the best results.

R. S. Glasgow: The authors mention the Hewlett type of loud speaker in their paper and point out that one of its disadvantages is the long air-gap that the radial magnetic field has to traverse, with the result that considerable energy is required for excitation purposes.

I would like to know whether the quality of reproduction would be effected by the substitution of a thin iron diaphragm in place of the non-magnetic materials that are usually employed.

A. Nyman (by letter): The conclusion the authors have drawn from physical considerations is that the resistance control is the ideal for loud speakers; meaning, of course, by the resistance control any control which is proportional to the velocity of the movement of the sound-generating surface. From the ordinary physical consideration the loud speaker can be regarded as an ordinary electric motor with certain peculiar load conditions capable of giving resonance at certain frequencies, elastic control below that frequency, and inertia control above that frequency. It is quite evident that a motor of this type would operate most satisfactorily if the elastic control and the inertia control could be so small as to be negligible compared to the actual load output. Considering the loud speaker from this point of view, it is also evident that if a loud speaker can be designed with a large efficiency that the resistance control will naturally follow.

The problem therefore comes down to the design of a sound-producing structure of such a nature that the energy input from the electrical instrument is converted largely into sound energy and only a very small percentage into elastic or inertia energy. It is also evident that a large horn properly designed in such a way as not to have any permanent resonant characteristics would form an ideal load on the loud speaker, but involves an unwieldy mechanical structure. It has to be quite long before it is suitable. The attempts carried out by the experimenters, using large conical diaphragms apparently discloses the fact that it is difficult to construct a large conical diaphragm that will avoid irregular movements and local resonance difficulties.

In future, the development will be probably in this direction; that is, the construction of a mechanical structure for radiating sound in the space.

Even under the best conditions the energy that can be radiated into the air with an average loudness of sound is quite small. From this it follows that the restoring force, due to the elastic control should be small, and the inertia force should be also small. This condition naturally leads to a low-frequency structure, but consisting of light enough parts to be capable of responding to high-frequency currents. The writers of this paper achieved this object by the construction of a moving-coil unit with a practically floating diaphragm, and a consequent natural frequency of around 100 cycles. It is, however, possible to achieve frequencies as low as this with the ordinary electromagnetic types of loud speakers, both the steel-diaphragm type and the moving-armature type.

In either of these types there are two forces opposing each other under normal operative conditions. These forces are the elastic forces in the diaphragm, and the magnetic pull of the magnets. Now, it is possible to adjust the relation between these two forces in such a way that the difference between them is quite small. The resulting natural frequency of the whole system is consequently also very small. This can be done without any sacrifice on the part of the strength of magnetization. As a matter of fact, it is necessary to choose a rather soft diaphram on the moving-iron type in order to achieve this magnetic balance.

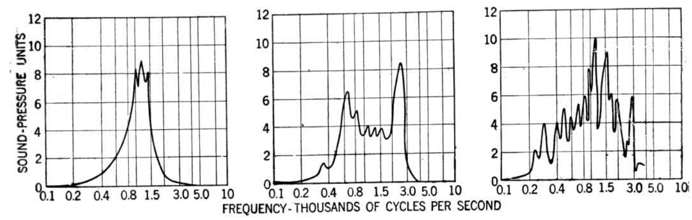


Fig. 1—For the Year 1921 Fig. 2—For the Year 1922 Fig. 3—For the Year 1923

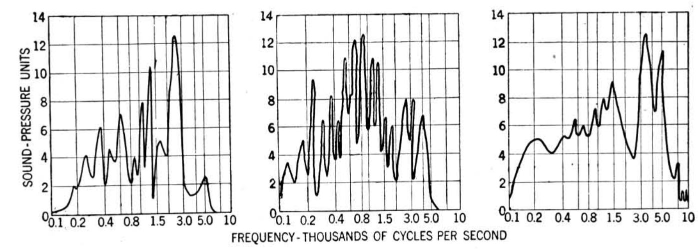
The sound-pressure measurements to which the writers refer at the end of the paper are undoubtedly still in a rather imperfect stage and can only afford comparative information on different types of loud speakers. It should be borne in mind, however, that under the best conditions the sound-pressure measurement will not give the complete information on a loud speaker. It is possible to choose a fairly resonant loud-speaker unit and a fairly resonant sound-diaphragm system, which in combination would give sound pressure measurements of almost constant value at different frequencies. However, this loud speaker will not necessarily give good musical or speech reproduction. There is a phenomenon which may be described as persistance of sound in all musical instruments; it has the same effect as the reverberation in large auditoriums, and is caused by the fact that resonance condition exists. This persistence causes the sound to continue radiating from the sound-distributing structure after the loud speaker has ceased to produce this sound. Of course, if the following note is of a different frequency from the persisting note, and possibly of a frequency causing a musical dissonance, the resulting sound would have a jarring effect in a musical composition. This phenomenon, which is not very well known, and as far as I know, has not been investigated by physical measurements, is however quite pronounced, and if precautions are taken to eliminate it, a considerable improvement in sound quality is possible.

J. P. Minton (communicated after adjournment): In a series of popular articles appearing during the past year in the *Wireless Age* I have pretty well covered the whole field of the ear, the voice and the loud speaker up to the present moment. As a result of this study and experimentation it is clear to me that up to the time, the loud speaker, in spite of improvements, has failed to give entirely satisfactory reproduction. Until the appearance of this new loud speaker, this device has been the weakest link in radio. In this respect radio has suffered in the past the same limitation that the phonograph has existed under. In phonograph reproduction the sound box and its associated horn were the weakest links. Recording was developed to an extent which made it possible to get into the record much more than the sound box and horn were able to give out. In a sense, radio reception has existed under the same impediment. However, radio originally was developed entirely for the transmission of intelligence and not for that of pleasure and entertainment. The requirements and sustaining forces in the two cases, therefore, were quite different. Accordingly, radio was developed to a high degree of perfection while the phonograph has not been so highly developed.

When radio broadcasting and reception came into existence, the already highly developed state of radio made possible the rapid growth of this new form of entertainment and education. The loud speaker had to be injected into this picture. Its use had previously been limited to certain fields of not very great importance. It had not received very serious consideration up to this point. Phonograph quality was quickly attained by use of horns of various sizes and shapes to which were attached units of the usual types. This stage was a temporary one, but it has existed for four or five years. In the meantime, a great deal of fundamental research was undertaken and now as a result of this work the loud speaker has been brought to a point where its performance is such as to make possible the reproduction of the original with an exactness astonishing to all of us.

As the authors have indicated the development has gone through a number of stages and in addition to their own excellent contribution to this work much credit for the gradual evolution of the loud speaker is due to many other workers in this and the allied fields of voice, ear and music analysis. Among the names of those who have contributed most from the fundamental point of view to this work will be found Rapleigh, Lamb, Webster, Stewart, Miller, Foley, from our universities and from our industrial research laboratories will be found such men, in addition to the present authors, as Hewlett, Slepian, Hanna, Fletcher, Wegel, Crandall, Maxfield, Goldsmith, Ringle, Wolff, Kranz and others.

From the scientific point of view it will be interesting to show a group of six curves which may represent the evolution of the loud speaker. The ordinates in these curves are proportional to sound pressures and the abscissas are frequencies divided by 1000. During the early stages (say 1921) of broadcasting, Curve 1 may represent an average loud speaker. Curve 2 may represent the state of the art in 1922. Curve 3 represents what was obtainable for 1923, Curves 4 and 5 for 1924 and Curve



Figs. 4—For the Year 1924 Fig. 5—For the Year 1924 Fig. 6—For the Year 1925

6 for 1925. These curves represent a steady progress in four or five directions. First, extension of the range of response to include both higher and lower frequencies. Second, uniformity of response, or the gradual elimination of the sharp peaks and depressions. Third, more nearly equal response at all frequencies. Fourth, reduction of non-linear distortion. Fifth, introduction of pure low-frequency response.

Curve 6 represents the performance of the new Rice-Kellogg loud speaker. The curve was taken close up to the loud speaker so that the characteristics of the vibrating system itself, actuated by a constant force, would be obtained. The loud speaker covers quite affectively a frequency range extending from 100 to

7500 and perhaps 10,000 cycles. The response is quite uniform compared with all other types of loud speakers and this new speaker gives an exceedingly small amount of non-linear response and therefore small distortion compared with all other loud speakers.

I wish to call attention to the fact that Curve 6 does not indicate complete agreement between the theory based on inertia action and the response at various frequencies. If the cone followed this simple theory then the response as measured by sound pressure should be constant at the various frequencies. Now, in this particular sample tested the response rises abruptly at 100 cycles; it also falls off abruptly above 6000 or 7000 cycles; there is also quite a marked depression in the region of 2000 cycles and a minor one at 4000 cycles. I am quite inclined to the view, therefore, that, in addition to the inertia-controlled motion which the authors seem to favor, there are also present to a marked extent flexural vibrations which, due to circular and diametral nodes of motion, corresponding to a plane membrane, produce the characteristics as indicated by the curve. We have studied these types of motion, for somewhat larger cones than the 6-in. one adopted by the authors, both theoretically and experimentally, and have found very curious nodes and interesting data which will prove of considerable practical value. At a later date we hope to have the opportunity to present these results.

E. W. Kellogg: Mr. Frederick has called attention to the fact that an inertia-controlled diaphragm implies a low-power-factor system, or one in which force and motion are nearly in quadrature, and therefore only a small fraction of the driving force is expended in the useful work of producing sound radiation. I have made a calculation which indicates that the efficiency of the loud speaker described in our paper is of the order of one per cent, which, it must be admitted is low, but compares very well with that of other loud speakers.

It may be of interest to review the possibilities of a sound reproducer in which the diaphragm motion is in phase with the driving force. Such a condition obtains when a diaphragm is in resonance, and efficiencies of 50 per cent or more are probably possible at a single frequency, using a resonant diaphragm. But when we impose the requirement of substantially constant efficiency over a frequency range of 100 to 5000 cycles, we must forego the benefits of resonance. The resistance-controlled diaphragm will have the correct radiation characteristic, 1—if it is large enough compared with the longest waves to give plane wave radiation, or 2—if it is used with a properly designed horn. For efficiency, the force which resists motion must be due to the air reaction on the diaphragm. In free space this air reaction is very small, and if it is to be large compared with diaphragm inertia or elastic forces, an extremely light and flexible diaphragm must be used. Such a diaphragm must be actuated by a uniformly applied force. Electrostatic loud speakers have been built with large-area diaphragms of very light material, and these have probably had quite high efficiency, if we define efficiency as the ratio of sound power output to electrical power input. But unfortunately we have to pay for the total volt-amperes supplied rather than simply for the electrical power, and the electrostatic loud speaker has a very low electrical power factor.

The case for the horn-type loud speaker has been discussed by Messrs. Hanna and Slepian[1]. By means of the horn the air reaction on the diaphragm can be increased to a point where it will effectively damp the motion of as stiff and heavy a diaphragm as is commonly employed in loud speakers. Thus a magnetically driven diaphragm may be used with resistance-controlled motion, or with a unity-power-factor relation between force and velocity. But a magnetic drive has good efficiency only when the motional impedance is a large part of the total impedance, or in other words, when as in the case of an electric motor, most of the impressed voltage is used in overcoming the counter electromotive force due to armature motion. A study of the motional impedance of magnetic telephones shows that only in the neighborhood of a resonance frequency is the motional impedance considerable compared with the resistance and inductive reactance, and if sufficient damping is introduced by the air reaction on the diaphragm to give substantially uniform response over a wide frequency range, the motional impedance becomes very small at all frequencies. This probably explains the fact that no horn-type loud speaker which we have tested shows any greater average efficiency than our inertia-controlled paper cone. I do not despair of considerably greater efficiencies being ultimately obtained in loud speakers, but from the standpoint of present progress in the art of sound reproduction, I do not believe that the adoption of inertia-controlled diaphragms can be construed as a step in the wrong direction.

Mr. Frederick raised the question of load capacity. The moving-coil drive has a distinct advantage over the iron-armature drive on this score. With the cabinet-set amplifier described in the paper, our loud speaker can easily reproduce vocal solos with the original sound volume, or can reproduce a piano selection as it would be played in a drawing room, though perhaps not with the maximum loudness that would be used in a large concert hall. The limit of loudness is set by distortion in the amplifier rather than in the loud speaker. In fact the latter will handle all the output which can be obtained without distortion from a U. V. 211 radiotron (50 watts oscillator rating) with a 1000-volt plate supply, or eight times the power obtainable from the cabinet-set amplifier.

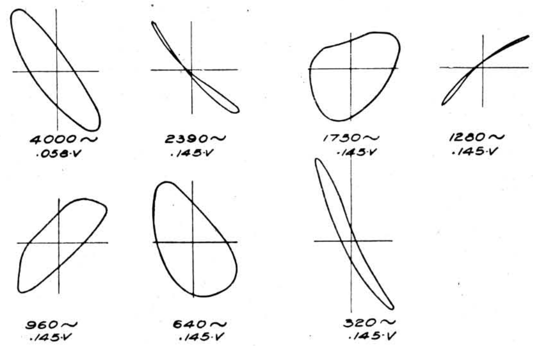


Fig. 7—Braun-Tube Records of Sound Waves

In stating that working with a weak magnetic field makes possible a lower net restoring force in the case of an iron-armature driving element, we made the assumption also made by C. R. Hanna in his January 1925 I. R. E. paper, that the magnetic reduction of stiffness cannot be more than a certain fraction (say 50 per cent) of the spring stiffness.

In comparing two loud speakers, we have rated the one as more sensitive which would produce on the average more total sound output from a given vacuum-tube source, both instruments being equally fitted to the tube impedance. In saying that the moving coil gives greater sensitivity than the iron-armature drive, we are reporting our experience with these types of drive as applied to paper-cone diaphragms.

Mr. McNamee asks about the use of permanent magnets for the field. When the loud speaker is combined with an amplifier, the dynamic field is hardly a drawback since the field winding acts as a necessary filter choke. We have done some experimenting with permanent magnets, but have not, up to the present succeeded in obtaining an adequate field for a moving-coil instrument without a very heavy magnet system.

Mr. Thelin asked about the material of the baffle. It should

1. The Function and Design of Horns for Loud Speakers, by C. R. Hanna and J. Slepian, Journal A. I. E. E., March 1924, page 250.

be stiff and heavy enough so that it will not readily be set in vibration by the air pressure. Wood, pressboard, and similar materials are satisfactory and convenient to use.

The question has been asked whether an iron diaphragm would increase the sensitivity of a Hewlett loud speaker. Dr. Hewlett found no gain from the use of iron, but instead, a distinct loss as compared with copper or aluminum. The increased flux density must be around, rather than in, the conductor in order to increase the force.

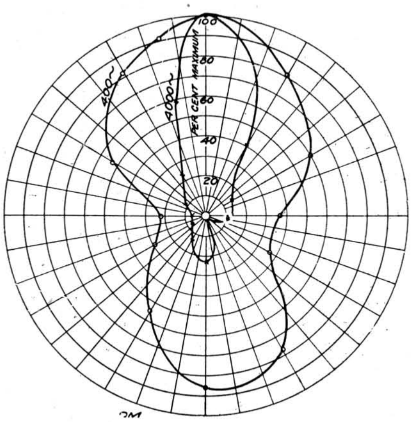


Fig. 8—Showing Sound Output of Loud Speaker at Different Positions

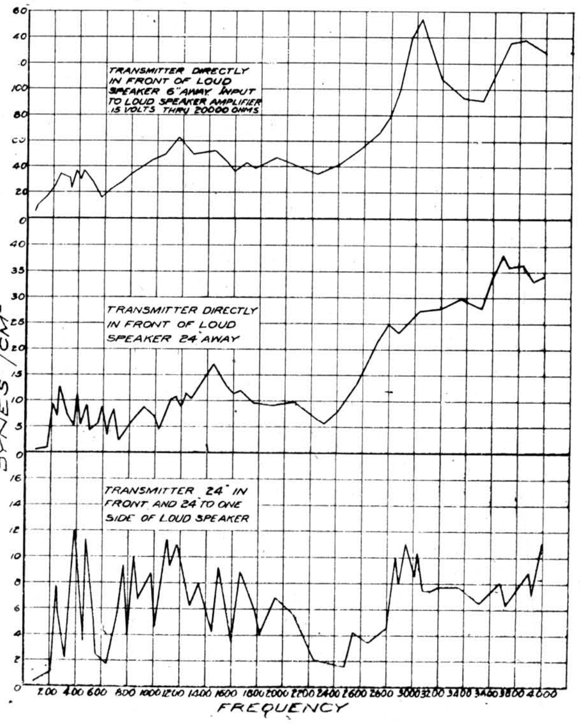


Fig. 9—Condenser Transmitter 34 in. from Center of Cabinet. Horizontal Directivity of Laboratory Model of Rice-Kellogg Loud Speaker, Per Cent Maximum Sound Pressure vs. Angle.

I am submitting as part of the discussion some sound-pressure curves which we have recently obtained. The measuring arrangements were still in the developmental stage when these curves were taken, and a high degree of accuracy is not claimed. In fact in acoustic measurements so great are the difficulties encountered that a measurement that can be trusted to be within 50 per cent of the correct value might be regarded as highly satisfactory. In the present case a condenser transmitter, with amplifier, detector, and galvanometer, was used for measuring sound pressure. The amplifier, detector and galvanometer system was calibrated by introducing a measured low voltage in series with the condenser transmitter. The condenser transmitter was similar in construction to that described by F. C. Wente in the *Physical Review*, July 1917, and May 1922. A calibration of the condenser transmitter was made by actuating its diaphragm by means of a special, laminated-pole telephone magnet held 1/16 in. from the diaphragm, the force being assumed to be proportional to the current through the coils. This does not give an absolute calibration, but should show any radical departure from the shape of the curve given in the *Physical Review* article already mentioned.

In loud-speaker tests it is important to guard against the error of crediting sound radiated in harmonics to the fundamental frequency. For example, if an instrument is supplied with a 200-cycle alternating current, and it happens to be one hundred times more sensitive at 400 and 600 cycles, than at 200, then a very small percentage of harmonics in the supplied current, plus harmonics produced in the instrument itself may give rise to a much larger radiation of 400- and 600-cycle sound than of 200-cycle sound. If the sound-measuring apparatus measures total r. m. s. pressure independent of frequency, considerable sound pressure will be indicated, and this would naturally be assumed to be 200-cycle output pressure.

To make sure that no serious error arose from this source, a Braun-tube oscillograph was set up. Between one pair of plates, a voltage was impressed, proportional to the current supplied to the loud speaker while a voltage from the condenser-transmitter amplifier, proportional to the sound pressure, was impressed across the other pair of plates of the Braun tube. If both voltages are sine waves, the figure which appears on the screen is an ellipse or an inclined straight line. Harmonics in one of the voltages result in deformations of the figure. In the present measurements, the oscillograph figure was watched throughout the entire range of frequency, and tracings were made of all the figures which were seriously distorted. In no case was it found that the harmonics carried more than 25 per cent of the energy of the fundamental in the output sound wave. Several samples of Braun-tube figures are shown here in Fig. 7.

The next serious problem in the testing of loud speakers results from the fact that the curve of sound pressure vs. frequency, changes in shape with change of microphone position. Which of the many possible positions will give a curve best representing what listeners on the average will hear? It would seem logical to avoid the irregularities due to standing waves in the room, and give a curve in which the sound pressure shown is a measure of the total sound power output. An approximation to this is obtained by averaging the square of the sound pressure over a considerable space by moving the microphone rapidly to and fro during each reading. Facilities for moving the microphone or transmitter in this manner were not available in our case and as an alternative, several curves are shown in Fig. 8 for different transmitter positions. The high or low regions which are common to all three curves may be interpreted as indicating large or small output from the loud speaker, while the irregularities which are different in the different curves are principally room effects. It will be noticed that the curves taken with the transmitter directly in front of the loud speaker show a marked increase in sound pressure above 2300 cycles. The instrument, however, has rarely been criticised on listening tests as having too much high-frequency output. The curve taken with the transmitter to one side, does not show such an excess of high tones. Evidently then the high sound pressures recorded in the upper frequency range are due in part to the concentration of the sound in a forward beam. The curves of Fig. 9 were taken by moving the transmitter in a circle and recording the sound pressure every 30 deg. They show the radiation at 4000 cycles to be sharply directed forward whereas at 400 cycles there is only a slight depression at the side due to interference between the waves from the front and back of the diaphragm. In total sound radiated, therefore, the excess of high frequencies is only slight. If high frequencies are lost in the transmitting or receiving systems, the listener prefers to take a place directly in front of the loud speaker, so as to get the full benefit of what is left, while if articulation is good, but there are roughnesses, or high-frequency disturbances present in the currents fed to the loud speaker, the listener will sit to one side.

It is probable that the frequency of 2300 cycles, where the forward projected sound begins to increase, marks the transition between the two modes of action of the cone. Below this frequency it acts as a unit or plunger while at higher frequencies there is wave action with some resonances. The depression in the region of 2300 cycles may correspond to the droop in the calculated curve in Fig. 10. This lends support to the belief that practical plunger action is maintained up to 2300 cycles. In the upper range, irregularities in the response may be expected not only from resonance in the cone, but also from the fact that the cone depth is appreciable compared with the sound wave length, and, therefore, the diaphragm no longer radiates like a flat plate.

The loss of output below 200 cycles is due to a decrease in the driving force. If the current through the moving coil is held constant the output sound pressure is practically the same at 80 as at 200 cycles, but in the curves shown here, it is the voltage supplied to the first stage of the amplifier which is maintained constant. The current through the moving coil then changes with changes in the coil impedance. This impedance rises from about 17 ohms at 200 cycles to over 80 ohms at 80 cycles and the consequent decrease in coil current results in reduced driving force and reduced sound output. The rise in impedance is due to the motion of the coil, which with inertia control becomes very large at low frequency.