Condenser and Carbon Microphones—Their Construction and Use *

By W. C. JONES

Of the numerous microphones which have been developed since Bell's original work on the telephone, only two are used extensively in sound recording for motion pictures, namely, the condenser microphone and the carbon microphone.

The condenser microphone was first proposed in 1881 but owing to its low sensitivity was limited in its field of usefulness until the development of suitable amplifiers. In 1917, E. C. Wente published an account of the work which he had done on a condenser microphone having a stretched diaphragm and a back plate so designed as to introduce an appreciable amount of air damping. The major portion of the condenser microphones used today in sound recording embody the essential features of the Wente microphone. Marked progress has, however, been made in the design and construction of these instruments with the result that they are not only more sensitive but also more stable. The factors which contribute to this improvement are described in detail in this paper. Recently a number of articles have appeared in the technical press calling attention to certain discrepancies between the conditions under which the thermophone calibration of the condenser microphone is made and those which exist in the studio. The nature of these discrepancies and their bearing on the use of the microphone are discussed.

Microphones in which the sound pressure on the diaphragm produces changes in the electrical resistance of a mass of carbon granules interposed between two electrode surfaces have been used commercially since the early days of the telephone. In recent years the faithfulness of the reproduction obtained with the carbon microphone has been materially improved by the introduction of an air damped, stretched diaphragm and a push-pull arrangement of two carbon elements. This instrument is finding extensive use in sound recording and reproduction fields where carbon noise is not an important factor. The outstanding design features of the push-pull carbon microphone are described in this paper and suggestions made as to the precautions to be taken in its use if the best quality, maximum life, etc. are to be obtained.

OF the numerous microphones which have been developed since Bell's original work on the telephone, only two are used extensively in sound recording for motion pictures, namely, the condenser microphone and the carbon microphone. It has therefore been suggested that it would be fitting to review at this time the construction of these instruments and consider some of their transmission characteristics and the precautions which should be exercised in their use.

Condenser Microphone

In 1881, A. E. Dolbear [1] proposed a telephone instrument which could be used either as an electrostatic microphone or receiver. This

* Presented at Soc. of Motion Picture Engineers' Convention, Oct. 20, 1930; Journal, Soc. of Motion Picture Engineers, Jan., 1931.

[1] "A New System of Telephony," A. E. Dolbear, *Scientific American*, June 18, 1881, p. 388.

instrument consisted of two plates insulated from one another and clamped together at the periphery. The back plate was held in a fixed position whereas the front was free to vibrate and served as a diaphragm. It is obvious that, if the diaphragm were set in vibration by sound pressure, the electrical capacitance between the two plates would be changed in response to the sound waves, and if a source of electrical potential were connected in series with the instrument a charging current would flow which would be a fairly faithful copy of the pressure due to the sound wave. Apparently Dolbear realized that the current developed in this way would be minute, for in the telephone system which he proposed as a substitute for the one using Bell's magnetic instruments he employed the electrostatic instrument only as a receiver and adopted the loose contact type of microphone. At approximately the same time an article appeared in the French press [2] calling attention to the use of a condenser as a microphone and commenting on the fact that this type of microphone had been found to be less sensitive than the loose contact type.

Owing to the low sensitivity of the condenser microphone, the field of usefulness of this instrument was extremely limited for a number of years and it did not assume a position of importance among the instruments used in acoustic measurements and sound reproduction until suitable amplifiers had been developed. The development of the vacuum tube amplifier, however, filled this need. In 1917 E. C. Wente [3] published an account of the work which he had done on an improved condenser microphone having a stretched diaphragm and a back plate so located relative to the diaphragm that in addition to serving as one plate of the condenser it added sufficient air damping to reduce the effect of diaphragm resonance to a minimum.[4] The response of this instrument was sufficiently uniform over a wide range of frequencies to make it not only useful in high quality sound reproduction but a valuable tool in acoustic measurements in general.

The major portion of the condenser microphones used today in sound recording embody the essential features of the Wente microphone. Marked progress has, however, been made in the design and construction of these instruments since the initial disclosure and it will no doubt be of interest to many to consider briefly the nature of this advance.

[2] "La Lumiere Electrique," 1881, p. 286.

[3] "A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity," E. C. Wente, *Physical Review*, July 1917, pp. 39–63. "Electrostatic Transmitter," E. C. Wente, *Physical Review*, May 1922, pp. 498–503.

[4] A discussion of the theory of air damping is given in "Theory of Vibrating Systems and Sound," I. B. Crandall, pp. 28–39.

In the early microphones employing air damping the diaphragm was composed of a thin sheet of steel which was stretched to give it a relatively high stiffness. When assembled in the microphone the stiffness was further increased by that of the air film between diaphragm and the damping plate with the result that the resonant frequency was well above the frequencies which it was desired to transmit and the diaphragm vibrated in its normal mode over a wide frequency range. In such a structure the mechanical impedance for frequencies below resonance is due almost entirely to stiffness reactance. Hence a constant sound pressure produces substantially the same displacement of the diaphragm at all frequencies within this range and uniform response results except at the very low frequencies where an appreciable reduction in the stiffness of the air film occurs. The effective mass of a steel diaphragm is, however, relatively large and necessitates a comparatively high stiffness to secure the desired resonant frequency. From the standpoint of securing maximum sensitivity of the microphone, i.e. displacement of the diaphragm per unit force, it is of course important to make the stiffness as low as possible and employ as small a value of mechanical resistance as is consistent with the degree of damping required. An improvement in both respects can be effected by decreasing the mass of the diaphragm for with a reduced mass a given resonant frequency can be obtained with lower values of stiffness and the desired damping constant secured with less mechanical resistance.

The aluminum alloys have therefore replaced steel in the diaphragms of most of the condenser microphones in use today. A typical example of such a microphone is the Western Electric Company's instrument (394-type) shown in the photograph, Fig. 1, and the cross-sectional view, Fig. 2. The diaphragm of this instrument is made from aluminum alloy sheet .0011 inch in thickness. The edges are clamped securely between threaded rings, gaskets of softer aluminum being provided to prevent damage at the clamping surfaces. The requisite stiffness is obtained by advancing the stretching ring until a resonant frequency of 5,000 cycles is obtained. The method of determining the resonant frequency of the diaphragm is as follows. The diaphragm assembly to be tested is coupled to a condenser microphone which is provided with a suitable circuit for measuring its output. A special telephone receiver is placed in contact with the diaphragm on the side opposite to the coupler. Current from a vacuum tube oscillator is then passed through the winding of the receiver, setting up eddy currents in the diaphragm under test. The forces which are developed as a result of the reaction of the magnetic field produced by the eddy currents and that of the permanent magnet of the receiver set the test diaphragm in motion. The resonant frequency is determined by noting the frequency at which the output from the condenser microphone is a maximum.

In the early Wente microphone the damping plate was a continuous surface. Subsequent work by I. B. Crandall[5] showed that the required amount of damping at the resonant frequency could be obtained without adding unduly to the impedance at other frequencies by cutting grooves in the plate. This reduced the stiffness introduced by the air film and decreased the irregularity in response at low frequencies previously mentioned. The grooves in the damping plate of the

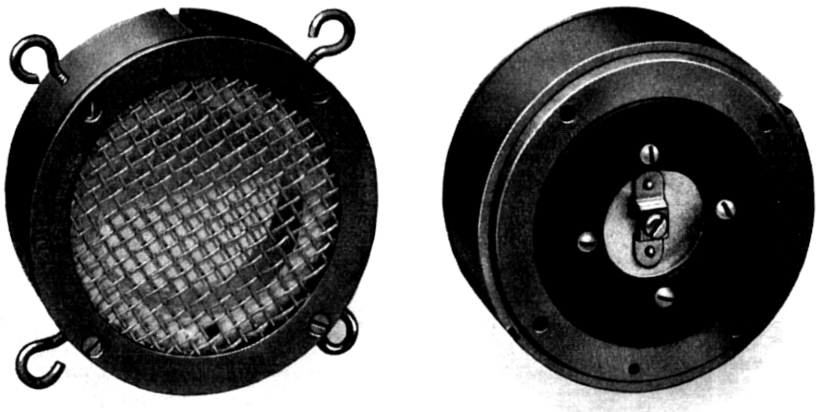

Fig. 1—Western Electric Company's 394-type condenser microphone.

Western Electric Company's 394-type microphone are cut at right angles. Holes, tapered at the outer end to reduce resonant effects, are bored through the plate at the intersection of the grooves to form connecting passages between the air film at the front and the cavity at the back. In order to prevent the resonance which would result if the grooves extended into the portion of the chamber surrounding the damping plate, the outer ends are closed by an annular ring which is pressed over a shoulder on the plate. The surface of the damping plate is plane within 8×10^{-5} inch. The departure from a plane in any individual case is determined commercially by the interference pattern developed when an optically flat plate is placed over the damping plate under test.

[5] "The Air Damped Vibratory System: Theoretical Calibration of the Condenser Transmitter," I. B. Crandall, *Physical Review*, June 1918, pp. 449–460.

A duralumin spacing ring .001 inch in thickness separates the damping plate from the diaphragm. It is essential that all dust and dirt be excluded from this space. To prevent foreign material from entering through the holes in the plate a piece of silk is fastened over the outer surface. The assembly of the diaphragm and the damping plate is made in a dust-proof glass cabinet.

If the back wall of the condenser microphone were rigid, changes in the separation between the damping plate and the diaphragm of sufficient magnitude to affect not only the sensitivity of the instrument but also its frequency response characteristic would result from variations in barometric pressure. Complete compensation for these

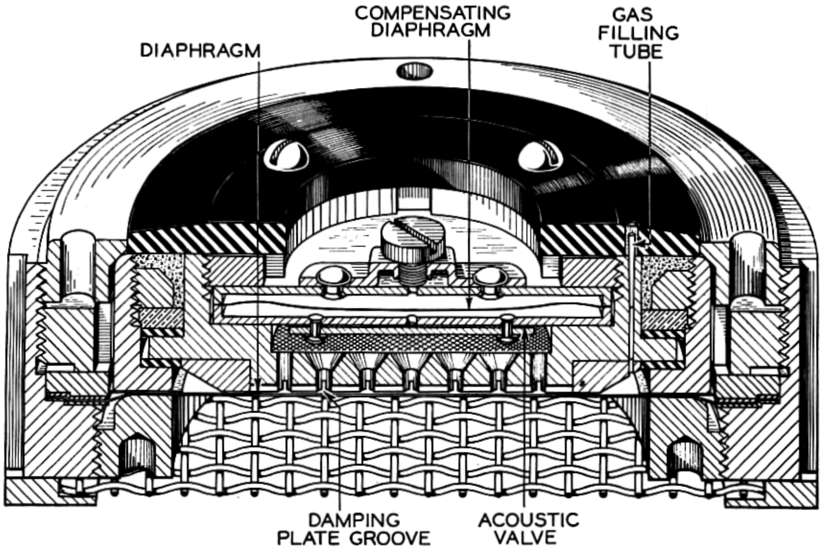

Fig. 2—Cross-sectional view of the 394-type condenser microphone.

changes in pressure can only be obtained by permitting free interchange of air between both sides of the microphone diaphragm. This is, however, objectionable owing to the fact that sufficient moisture is likely to be introduced to start corrosion and affect the insulation between the damping plate and the diaphragm. A compensating diaphragm of organic material has therefore been introduced which prevents this undesirable effect of humidity but is sufficiently low in stiffness to equalize the changes in pressure encountered in the normal use of the microphone.

In order to prevent transmission losses at voice frequencies due to the presence of the compensating diaphragm, an acoustic valve is inserted between the damping plate and this diaphragm. This valve consists of a disc of silk clamped between two aluminum plates of unequal diameters. Gas in passing from the damping plate to the compensating diaphragm moves laterally from the edge of the smaller plate through the silk to a hole in the center of the larger plate. The impedance of this path is high at voice frequencies but low enough for steadily applied pressure differences to permit compensation for changes in barometric pressure.

After the damping plate and diaphragm are assembled the space between the clamping rings is filled with beeswax to make the joints gas-tight and exclude moisture. A hole is, however, provided for filling the microphone with nitrogen. The purpose of the nitrogen is to prevent corrosion of the damping plate and diaphragm surfaces and eliminate any reduction in pressure due to oxidation of the sealing compound.

It has been customary for some time to determine the response characteristics of a condenser microphone by the thermophone method.[6] In making this measurement the diaphragm of the microphone is coupled acoustically to the thermophone in the manner shown in Fig. 3. The thermophone consists of two strips of gold foil

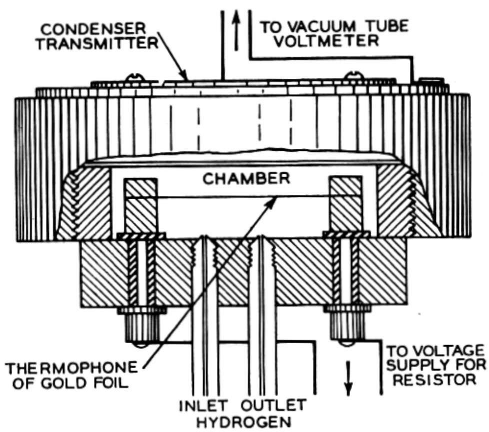

Fig. 3—Cross-sectional view of the thermophone and the condenser microphone.

which are mounted on a plate and fit into the recess in the front of the microphone. Capillary tubes are provided for filling the space enclosed between the plate and the microphone diaphragm with

[6] "The Thermophone as a Precision Source of Sound," H. D. Arnold and I. B. Crandall, *Physical Review*, July 1917, pp. 22–38. "The Thermophone," E. C. Wente, *Physical Review*, April 1922, pp. 333–345. "Speech and Hearing," H. Fletcher, 1929, Appendix A.

hydrogen. This is done in order to make the wave-length of the sound developed in the recess as large as possible compared with dimensions of the chamber. If this were not the case the sound pressure at different positions in the chamber would not be in phase and the conditions on which the computations of the magnitude of the sound pressure are based would not be met. A direct current of known value is passed through the foil. Superimposed upon the direct current is an alternating current of the desired frequency which causes fluctuations in the temperature of the foil and in the gas immediately surrounding it. These fluctuations in temperature in turn cause changes in the pressure on the microphone diaphragm. The magnitude of the pressure developed on the diaphragm can be computed from the constants of the thermophone and the coupling cavity, and the voltage developed by the microphone for a given pressure determined with suitable measuring circuits.[7] Obviously, such a calibration affords a measure of the response of the microphone in terms of the actual pressure developed on the diaphragm and is independent of the external dimensions of the instrument. Hence, it does not take into account any effect which the microphone may have on the sound field when used as a pick-up instrument for recording or broadcasting purposes. The thermophone calibration is often referred to as a "pressure" calibration and the response obtained by placing the instrument in a sound field of constant pressure, a "field" calibration. A thermophone calibration of a representative Western Electric 394-type condenser microphone is shown on Fig. 4.

For many of the uses to which the condenser microphone is put, for example the calibration of head type telephone receivers, the conditions under which it operates agree with those under which the thermophone calibration is made. There are, however, cases where this agreement does not exist, for when a microphone is inserted in a sound field of uniform intensity the pressure on the diaphragm may depart rather widely from a constant value in certain frequency ranges. Several articles [8] have recently appeared calling attention to this discrepancy between the pressure and field calibrations and pointing out that a pressure calibration of a microphone may not be entirely representative of its performance under the conditions which exist in a studio.

[7] "Master Reference System for Telephone Transmission," W. H. Martin and C. H. G. Gray, *Bell System Technical Journal*, July 1929, pp. 556–559.

[8] "The Use of a Wente Condenser Transmitter to Measure Sound Pressures in Absolute Terms," A. J. Aldridge, *P. O. E. E. Journal*, Oct. 1928, pp. 223–225. "Effect of the Diffraction Around the Microphone in Sound Measurements," S. Ballantine, *Physical Review*, Dec. 1928, pp. 988–992. "Measurements of Sound Pressure on an Obstacle," W. West, *Inst. Elec. Eng. Journal*, 1929, pp. 1137–1142.

The difference between the pressure and field calibrations is due to several factors. In the first place the sound is diffracted around the microphone differently at different frequencies. At frequencies where the wave-length is large as compared with its external dimensions the pressure is the same as that of the undisturbed wave. At the higher frequencies where the microphone is large in comparison with the wave-length of the sound, the pressure is twice that developed at the lower frequencies. In the 394-type microphone the effect of diffraction

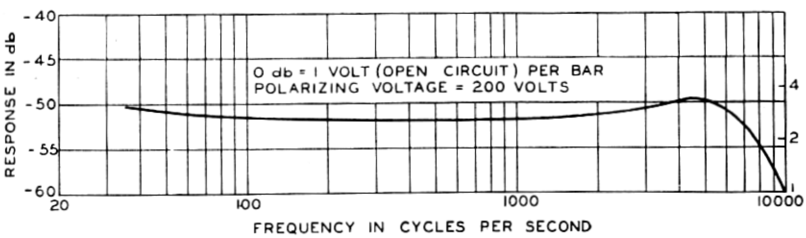

Fig. 4—Pressure calibration of the 394 type condenser microphone.

first becomes noticeable in the region of 1200 cycles and reaches a maximum of 6 db at approximately 2200 cycles. The second factor which causes a difference between the pressure and field calibrations is acoustic resonance in the shallow cavity in front of the microphone. This causes the pressure actuating the diaphragm to be higher than that of the incident sound wave in the frequency region of 1500 to 5500 cycles. The maximum increase in pressure occurs at approximately 3500 cycles. If the sound source is so located relative to the

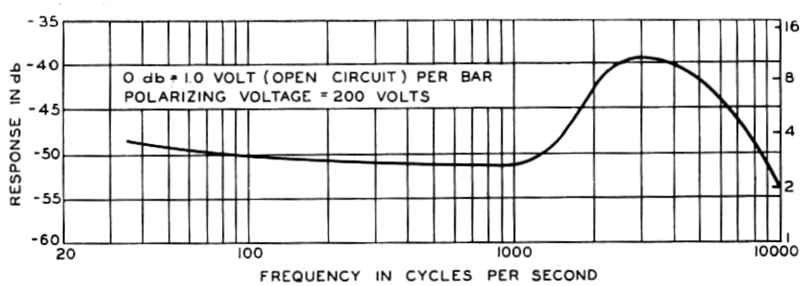

Fig. 5—Field calibration of the 394-type condenser microphone for a direction of approach of sound normal to the diaphragm.

microphone that the waves approach from a direction normal to the diaphragm and reflection from surrounding walls and objects is negligible, the combined effect of diffraction and resonance is to produce a maximum departure from flatness of approximately 12 db as is shown by the field calibration Fig. 5.[9] If the sound wave travels

[9] These curves are taken from unpublished work of P. B. Flanders of the Bell Telephone Laboratories, Inc.

along the diaphragm the effective pressure is reduced at the higher frequencies due to difference in phase. Hence, if the direction of approach of the sound wave is parallel to the plane of the diaphragm, the departure from flatness is materially reduced. This is brought out quite clearly by the field calibration for sound approaching from a direction parallel to the diaphragm, Fig. 6.[9]

The discrepancy between the pressure and field calibrations of the condenser microphone involves two important assumptions, namely, a plane sound wave and no reflection from walls or surrounding objects. When the microphone is used in a studio much of the sound reaches the diaphragm by way of reflection from the walls of the room. The requirement of no reflection is therefore not met and the influence of the acoustic properties of the reflecting surfaces is added to the characteristics of the microphone. The effect of the diffusion of the

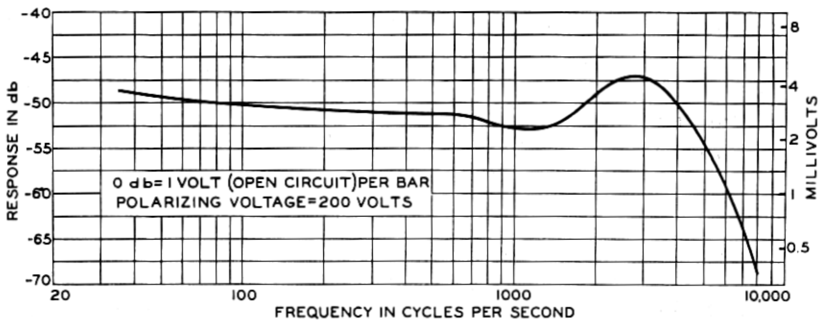

Fig. 6—Field calibration of the 394-type condenser microphone for a direction of approach of sound parallel to the diaphragm.

sound field and the tendency for most materials to be more absorbent for sounds of high frequency appears to cause the response under studio conditions to be more nearly like that obtained when the sound approaches in a direction parallel to the diaphragm and make the departures from the pressure calibration less marked than the field calibration for a direction normal to the diaphragm would indicate. This perhaps accounts in part at least for the instances in which a corrective network designed to compensate for the field calibration normal to the diaphragm failed to effect a material improvement in quality.

The acoustic conditions under which a microphone is used cover a wide range. It would therefore be difficult if not impossible to adopt a set of conditions for use in connection with a field calibration of the condenser microphone, which would be known to be representative of those encountered in practice. The pressure method of calibration on the other hand is definite, simple, and capable of being accurately duplicated in different laboratories. In view of this situation it would seem advisable to retain, at least for the present, the thermophone or pressure method of calibration for general use. In cases where precise quantitative measurements are required a field calibration of the microphone should of course be secured under the conditions of actual use. Various methods of making such a calibration have been proposed. The Rayleigh disc has been used extensively in this work thus far but there are certain very definite limitations to the extent to which it can be applied. An interesting discussion of the use of the Rayleigh disc may be found in papers by E. J. Barnes and W. West,[10] and L. J. Sivian.[11]

It would seem reasonable to expect that future design work would be directed toward reducing transition, resonance and phase difference effects to a minimum. The results of work along this line have been reported by S. Ballantine [12] and D. A. Oliver.[13] In both instances the mechanical design is such that the resonant cavity in front of the diaphragm is eliminated and the housing is spherical or streamline to reduce the diffraction effect. There has as yet been little opportunity to determine the extent of the practical improvement effected by these changes in design and the whole discussion continues to be somewhat academic in character.

Carbon Microphone

Bell's original microphone was essentially a generator and hence was limited in its output to the maximum speech power available at its diaphragm. The demand for telephonic communication over longer distances led to the early introduction of a carbon microphone. In this instrument the resistance of the carbon element is caused to vary in response to the sound pressure on the diaphragm and produces changes in the current supplied from an external source of electrical potential, which are fairly faithful copies of the pressure changes which constitute the sound wave. The carbon microphone is therefore in general an amplifier in which a local source of power is controlled by the acoustic power of the sound wave.

The carbon element or "button" of the first microphones (Edison, 1877) was made from plumbago compressed into cylindrical form.

[10] "The Calibration and Performance of the Rayleigh Disc," E. J. Barnes and W. West, *Inst. of Elec. Eng. Journal*, 1927, Vol. 65, pp. 871–880.

[11] "Rayleigh Disc Method for Measuring Sound Intensities," L. J. Sivian, *Philosophical Magazine*, March 1928, pp. 615–620.

[12] Contributions from the Radio Frequency Laboratories No. 18, S. Ballantine, April 15, 1930.

[13] "An Improved Microphone for Sound Pressure Measurements," D. A. Oliver, *Journal of Scientific Instruments*, April, pp. 113–119.

This type of button was relatively insensitive and shortly after its introduction the suggestion (Hunnings, 1878) was made that the space between the diaphragm and the fixed electrode be "partially filled with pulverized engine coke," [14] in order to increase the number of contact points and render them more susceptible to the forces developed by the motion of the diaphragm. When at its best the Hunnings transmitter was fairly efficient but at times was erratic in its performance due in part to the nature of the microphonic material. In 1886 Edison [15] proposed the use of granules of hard coal which had been heat treated. This was an important advance, for carbon made from anthracite coal is used not only in the microphones which are being considered in this paper but in commercial telephone transmitters as well.

As in the case of the condenser microphone, the displacement of the diaphragm of the carbon microphone must be substantially constant at all frequencies if uniform response is to be obtained. In the early microphones of the carbon type, diaphragm resonance introduced rather prominent irregularities in response. Air damped stretched diaphragms offered one solution of this problem. During the World War instruments of this type were developed and applied to the problem of locating airplanes. In 1921 double button stretched diaphragm microphones were made available for use with the public address equipment installed for the inaugural address of President Harding and the excercises at Arlington on Armistice Day.[16] The carbon microphones employed in sound picture recording are of the stretched diaphragm double button type. The electrical output from this type of microphone is not only of substantially uniform intensity over a wide frequency range but due to the "push-pull" arrangement of the buttons is comparatively free from harmonics. A typical example of the present day carbon microphone is shown in the photograph, Fig. 7. Fig. 8 is a cross-sectional view of the same type of microphone.

The diaphragm is made from duralumin .0017 inch in thickness and is clamped securely at its outer edge. The clamping surfaces are corrugated and emery cloth gaskets are provided to prevent slipping. The stretching of the diaphragm is done in two steps. The initial stretching ring is first advanced by means of six equally spaced screws until the diaphragm is smooth and free from irregularities. The inner or final stretching ring is then adjusted to a position which gives the

[14] "Beginnings of Telephony," F. L. Rhodes, p. 79, 1929.
[15] U. S. Patent No. 406,567, 1889.
[16] "Public Address Systems," I. W. Green and J. P. Maxfield, *A. I. E. E. Journal*, April 1923, pp. 347–358.

diaphragm a resonant frequency of 5700 cycles per second. The method employed in making the determination of the resonant frequency is substantially the same as that used in connection with the assembly of the condenser microphone, with the exception that the

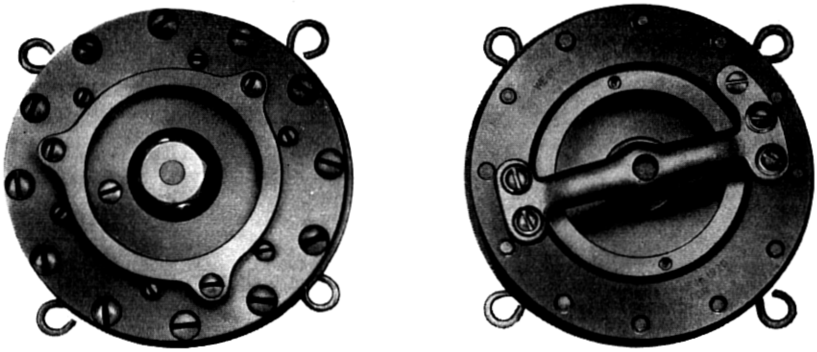

Fig. 7—Western Electric Company's 387-type carbon microphone.

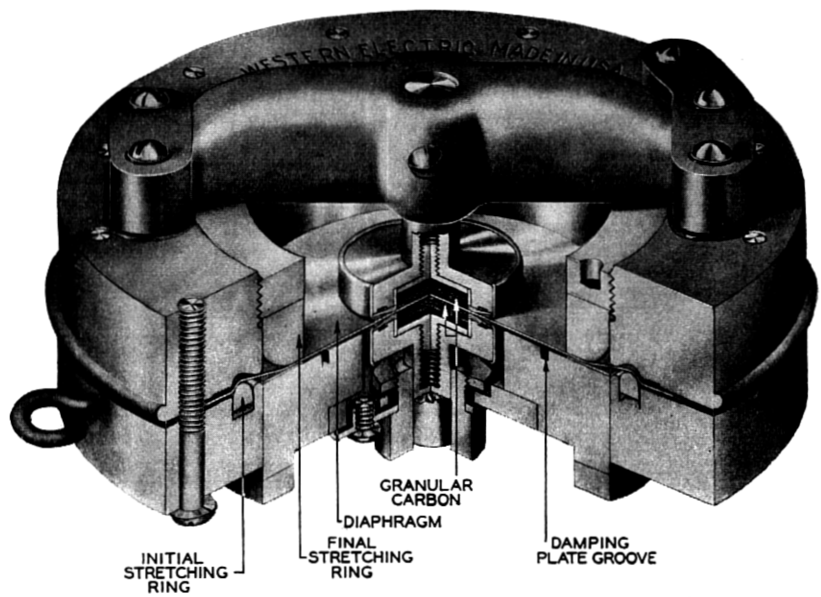

Fig. 8—Cross-sectional view of the 387-type carbon microphone.

frequency at which the maximum output occurs is usually determined by ear rather than by the coupler method previously described. In order to insure a uniformly low contact resistance the portions of the diaphragm which are in contact with the granular carbon are covered with a film of gold deposited by cathode sputtering.

A spacing washer .001 inch in thickness separates the diaphragm from the damping plate. A single concentric groove is provided in the damping plate.

The buttons are of the conventional cylindrical type but are provided with a novel form of closure to prevent carbon leakage at the point where they make contact with the diaphragm. The closure consists of twenty-seven rings of .0004 inch paper clamped firmly together at the outer edge and spreading apart at the inner edge to form a structure which effectively seals the junction between the diaphragm and the buttons without adding materially to the mechanical impedance.

As has already been pointed out the granular carbon is made from selected anthracite coal. The size of the granules is such that they will pass through a screen having 60 meshes per inch but will be retained on a screen having 80 meshes per inch. Before heat treatment the raw material is treated with hydrofluoric and hydrochloric acids to reduce the ash content. Each button contains .060 cc. of carbon, i.e., about 3000 granules.

The bridge which supports the button on the front of the diaphragm partially closes the acoustic cavity on that side. It is essential, therefore, that it be so proportioned as to have a minimum reaction on the response of the microphone and yet provide the required degree of rigidity. It was this consideration that led to the smooth stream line contour now employed.

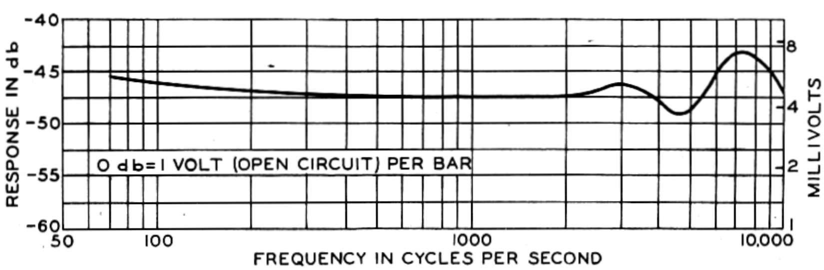

Fig. 9—Pressure calibration of the 387-type carbon microphone.

Referring to Fig. 9 it will be observed that the adoption of an air damped stretched duralumin diaphragm for the carbon microphone has resulted in an instrument having a substantially uniform response over a wide range of frequencies. The arrangement of the apparatus employed in securing the data from which this curve was plotted is shown in the photograph, Fig. 10. The microphone under test was mounted in a highly damped room at a distance of six to eight feet from a source of sound which consisted of two loud speaking receivers.

One of the receivers was the conventional form of moving coil direct radiator and was used to provide sound in the lower frequency range. The other was a special moving coil receiver with a short horn so designed as to serve as an efficient source of sound up to 10,000 cycles.[17] To reduce the effect of standing waves the mounting for the receivers was so constructed that they could be rotated through a circle approximately five feet in diameter and always face the microphone under test. Before starting the test of the carbon microphone the receivers were calibrated by placing a calibrated condenser micro-

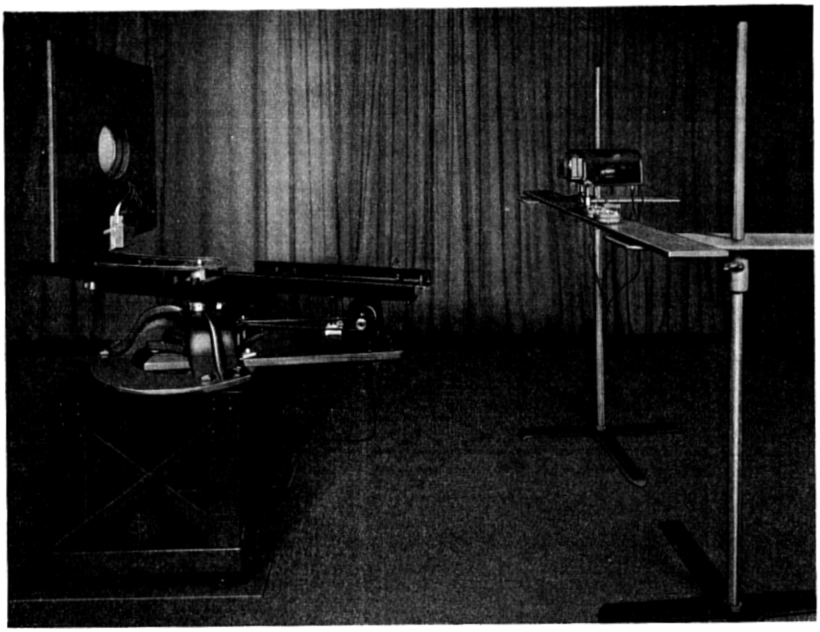

Fig. 10—Apparatus employed in calibrating the 387-type carbon microphone.

phone at the point where the test instrument was to be located and determining the receiver current required to produce a pressure of one bar (one dyne per square centimeter) on the microphone diaphragm. The condenser microphone was then removed and the test microphone substituted. The open circuit voltage developed by the microphone when supplied with a direct current of .025 ampere per button was then measured. The data obtained in this way are essentially a "pressure calibration" of the microphone and in interpreting them in terms of "field" performance the same factors must be taken into account

[17] "An Efficient Loud Speaker at the Higher Audible Frequencies," L. G. Bostwick, *Journal of the Acoustical Society*, Oct. 1930, pp. 242–250.

which have been discussed in considerable detail in connection with the condenser microphone.

The circuit employed in measuring the response of the carbon microphone is shown on Fig. 11. Two steps are involved in the calibration of the sound source. With the output terminals of the microphone circuit and the sound source short circuited and the polarizing voltage for the condenser microphone removed, the attenuator is adjusted until the voltage applied to the measuring circuit is that developed by the condenser microphone when a sound pressure of one bar is impressed on its diaphragm. A record is made of the reading of the

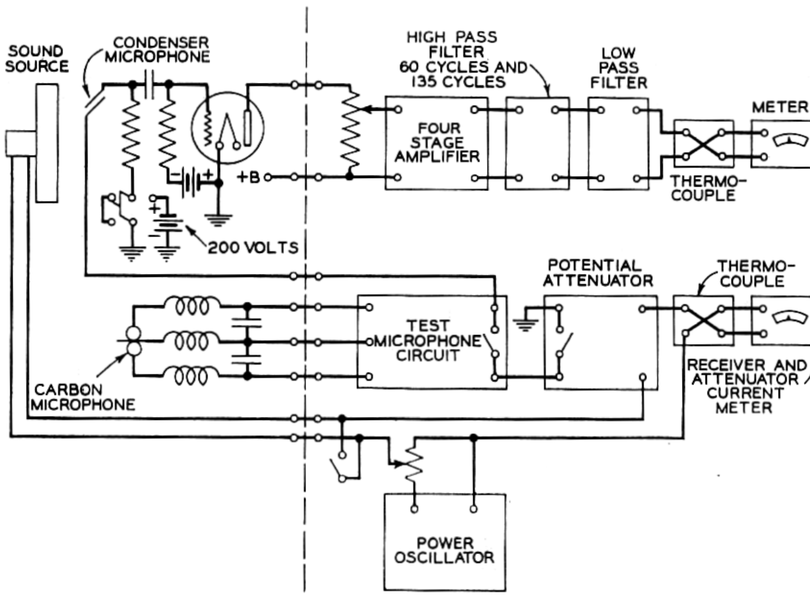

Fig. 11—Circuit employed in calibrating the 387-type carbon microphone.

output meter in the measuring circuit. The polarizing voltage is then applied to the condenser microphone. After the output terminals of the attenuator have been short circuited an alternating current of a known frequency is supplied to the sound source and the magnitude of this current adjusted until the meter reading is the same as that previously obtained with the attenuator. This completes the calibration of the sound source for that frequency. After the carbon microphone has been placed in the position previously occupied by the condenser microphone, the polarizing voltage is once more removed from the condenser microphone and the output from the carbon microphone circuit impressed on the measuring circuit. The reading of the output meter is recorded. The sound source and carbon microphone circuit are then short circuited and the output from the attenuator again applied to the measuring circuit. The attenuator is adjusted until the reading of the output meter is the same as was previously obtained with the carbon microphone in circuit. In this way the voltage applied to the measuring circuit when the carbon microphone is in operation is determined. The open circuit voltage developed by the carbon microphone may then be computed from the voltage and the constants of the microphone circuit. At the locations where these measurements were made a certain amount of interference from 60-cycle circuits and low frequency acoustic disturbances was encountered. The high-pass filter in the measuring circuit was introduced to facilitate the measurements under these conditions. The adjustable low-pass filter was used to confine the measurements to the fundamental frequency. Only that portion of the apparatus to the left of the dotted line was mounted in the damped room.

The two buttons of the carbon microphone are identical in their dimensions and if the granular carbon is in the same mechanical state have substantially the same electrical characteristics. They are also practically free from the cyclic variations in resistance known as "breathing" which result from the temperature changes caused by the power dissipated in the granular carbon. It is, however, a matter of every day experience that a given mass of granular material will occupy different volumes, depending upon the configuration of the particles. In the case of microphone carbon this change in configuration of the granules results in changes in the contact forces of sufficient magnitude to affect the resistance and sensitivity. If these changes occur in unequal amounts in the buttons electrical unbalance results. When complete balance exists the electrical output is free from all harmonics introduced by the circuit. Hence, in using the microphone care should be taken to see that a fair degree of balance between the buttons is maintained.

The performance of a carbon microphone may be affected adversely by cohering of the granules. Severe cohering is accompanied by a serious reduction in resistance and sensitivity which persists for an extended period unless the instrument is tapped or agitated mechanically. One of the common causes of cohering is breaking the circuit when current is flowing through the microphone. Experiment has shown that the insertion of a simple filter consisting of two .02 mf. condensers and three coupled retardation coils each having a self-inductance .0014 henry, will effectively protect the microphone button from cohering influences without introducing an appreciable transmission loss. This filter may be located in the base of the mounting or in a container fastened to the back of the microphone.

Aging of granular carbon may result from changes in the contact surface caused either by mechanical abrasion or overheating due to excessive contact potentials. Aging is usually accompanied by an increase in resistance and loss in sensitivity. Care should therefore be exercised in the use of the carbon microphone that it is not subjected to unnecessary vibration which would cause the granules to move relative to one another and abrade the surfaces. The use of abnormally high voltages should also be avoided.

The quality of transmission obtained with the double button carbon microphone compares favorably with that secured with a condenser microphone. The carbon microphone also requires less amplification. There is, however, one characteristic which limits its use, namely carbon noise. The level of the noise is much higher than that due to thermal agitation within the carbon granules [18] and appears to be caused by heating at the contacts between the granules. A certain amount of gas is contained in the pores in the contact surfaces. When current passes through the button, a sufficient increase in contact temperature takes place to cause a portion of this gas to be driven off and produce the non-periodic changes in resistance which give rise to carbon noise.

In conclusion it may be stated that the condenser and carbon types of microphones have been developed to a point where there is little to choose between them from the standpoint of quality of transmission. The design from a mechanical standpoint has also been carried to a point where little difficulty should be experienced in their use if reasonable precautions are exercised. Although requiring less amplification than the condenser microphone the extent to which the carbon microphone is used at present is limited by the higher noise level obtained. The condenser type of microphone has therefore been adopted for most of the recording work in the sound picture field.

[18] "Thermal Agitation of Electricity in Conductors," J. B. Johnson, *Physical Review*, July 1928, pp. 97–109.