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The Carbon Microphone: An Account of Some Researches Bearing on Its Action *

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A great variety of speculations in regard to the physics of microphonic action has arisen because of the complexity of behavior when current passes through a so-called "loose contact" which forms the essential element in a carbon microphone. Technical difficulties arising from the minuteness of the contact forces and movements between contacts when in a sensitive microphonic state have retarded the establishment of a quantitative theory.

Recent studies of carbon contacts have led to a satisfactory picture of the nature of such contacts and their mode of operation when strained, both from the elastic and the electrical point of view. The surfaces of the carbon particles are microscopically rough and when two such surfaces are brought together under the action of compressional forces, both the number of hills in intimate contact and the contact area between hills vary through deformations which are primarily elastic. Changes in electrical resistance under strain are consistent with the assumption that current passes through the regions in intimate contact.

Introduction

FEW electrical devices are as widely used as the "carbon microphone" and few have given rise to as much speculation in regard to their mode of action. That the problem has proved elusive is shown by the fact that in Bell Telephone Laboratories it has been regarded as perennial. However, recent researches have thrown a considerable amount of light upon it and it therefore seems fitting to bring before you this evening a brief survey of the subject and an account of some of the latest experimental work.

The widespread use of the "carbon microphone"—it is employed almost exclusively throughout the world in commercial telephone service—is due primarily to its unique property of being its own amplifier. In converting acoustical into electrical waves, it magnifies the energy about one thousandfold. Other microphones, such as the condenser or electromagnetic type, are unable to do this and so require separate amplifiers when used in practice. For this reason, it seems unlikely that the carbon microphone will be supplanted in the near future for at least the great bulk of telephone work.

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The essential element of this device is what has come to be called the "loose contact"—or, as its name implies, a contact between two conductive solids, metals as well as carbons, held together with small forces. The ability of "loose contacts" to transmit speech was discovered independently by Emile Berliner in this country and Professor D. E. Hughes in England. Following Hughes' discovery, Mr. Spottiswood, the president of the British Association in 1878, described it thus: "The microphone affords another instance of the unexpected value of minute variations—in this case, electric currents; and it is remarkable that the gist of the instrument seems to be in obtaining and perfecting that which electricians have hitherto most scrupulously avoided, viz., 'loose contacts.'" Hughes applied the word "microphone" to his instrument because of its remarkable "ability to magnify weak sounds." The word itself is a revival of a term first introduced by Wheatstone in 1827 for a purely acoustical device developed to amplify weak sounds. Although originally confined to the "loose contact" type of instrument, the term microphone has more recently been used—particularly in broadcast, public address, and sound picture work—for any device which converts sound into corresponding electric currents.

Evolution of the Carbon Microphone

The story of the development of the "loose contact" type of microphone is a fascinating one and, although it is beyond the scope of this

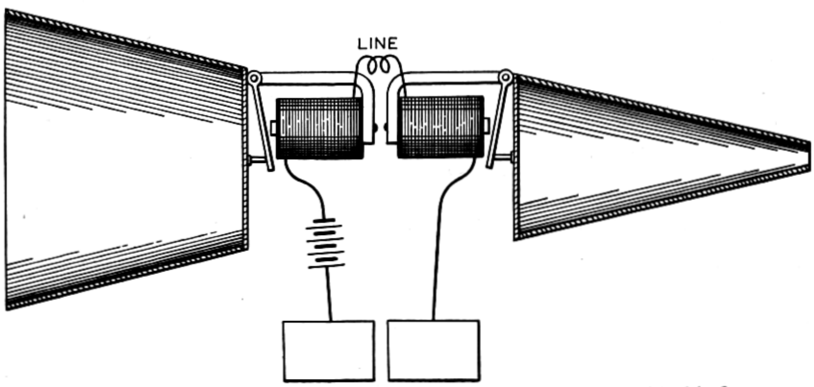

Fig. 1—Sketch, illustrating Bell's conception of the telephone, used in his first patent application of 1876.

paper,[1] I should like to refer briefly to a few of the stages in the evolution of the present day instrument. You will recall that Bell's original telephone (Fig. 1) was electromagnetic in principle and acted

[1] For a more complete account see paper by H. A. Frederick, "The Development of the Microphone," *Bell Telephone Quarterly*, July, 1931.

both as a transmitter and as a receiver. It was, however, very inefficient and Bell himself suggested that some other principle such as that of variation of electrical resistance might overcome the difficulty. He therefore devised the liquid transmitter in which a small platinum wire (Fig. 2), attached to a drumhead of gold-beaters

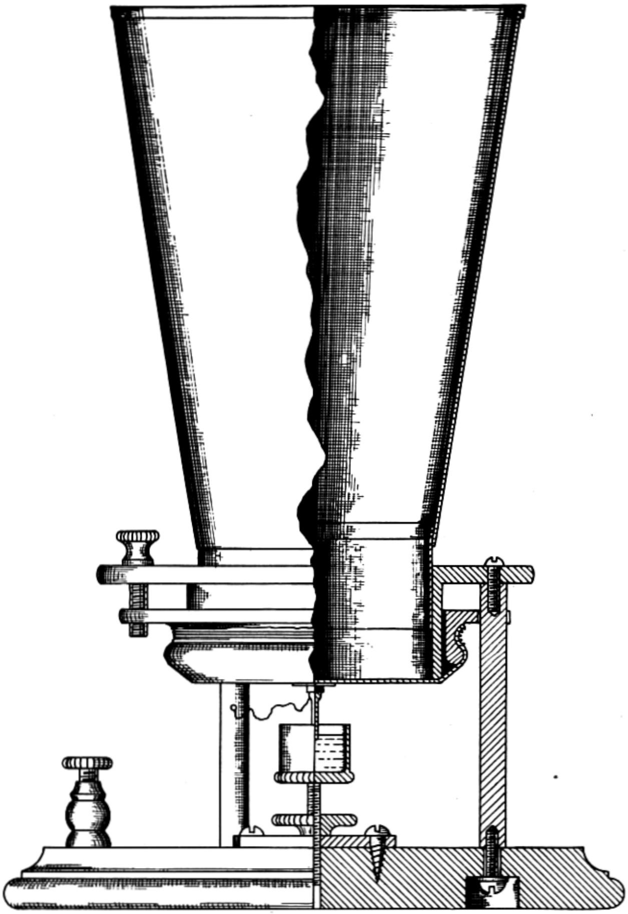

Fig. 2—Bell's liquid transmitter.

skin, is dipped into a small quantity of acidulated water in a conducting cup. The extent of the area of contact between the liquid and the wire is altered by the motion of the latter, thus altering the resistance in a continuous manner. It was with this instrument that the first complete sentence, "Mr. Watson come here—I want you," was successfully transmitted on March 10, 1876. This achievement stimulated others to work on the problem of a variable resistance element and many new devices appeared in the next few years, the most sensitive of which utilized a single loose contact, carbon in one form or another being used as the contact material.

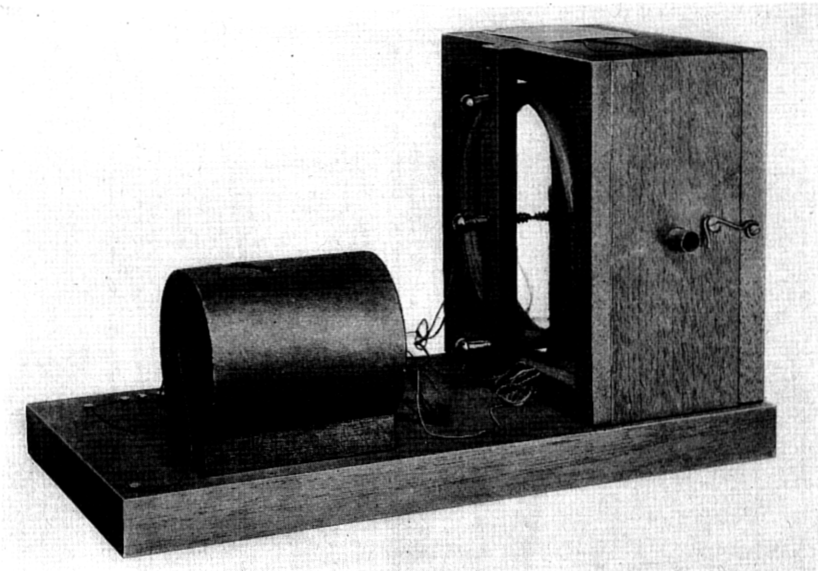

Fig. 3—Berliner's first single contact microphone, invented in 1877, employing a metal-to-metal contact.

Figure 3 shows Berliner's first successful model consisting essentially of a metal contact pressed against a metal diaphragm. This was developed later into a carbon-to-carbon contact along the same lines (Fig. 4).

Hughes, too, used metal in his first successful attempt at transmitting sounds. Only three ordinary nails were required to demonstrate the great sensitivity of loose contacts to acoustical vibrations (Fig. 5). Hughes later developed the pencil type of microphone (Fig. 6) in which carbon was used. It was the forerunner of many practical devices developed along this line.

More rugged, reliable and permanent than either of these types was the Blake transmitter shown in Fig. 7. It utilized a metal-to-carbon contact and it owed its success to the mechanical control of the contact pressure. This instrument was used for many years by the Bell System.

Then came the Hunnings or the first of the granular carbon microphones (Fig. 8), the immediate ancestor of the granular carbon type used today. Hunnings used powdered "engine coke." It carried

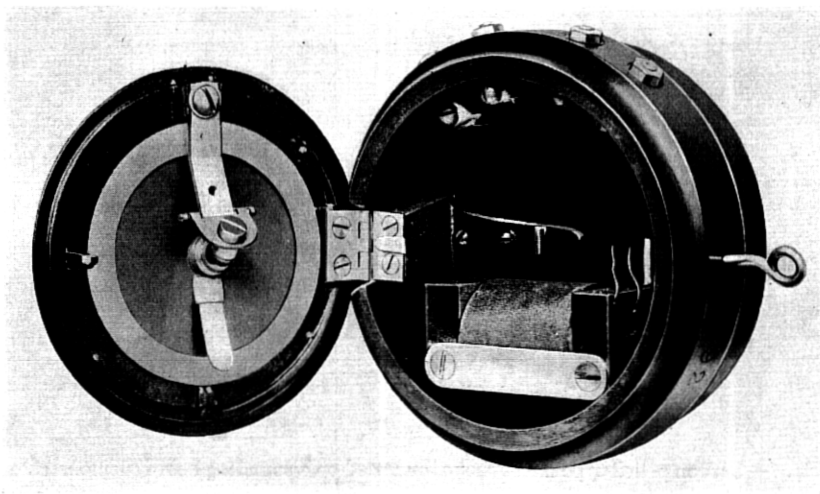

Fig. 4—Carbon-to-carbon single contact transmitter brought out in 1879 by Berliner.

more current than the Blake transmitter but it was liable to "pack" and become insensitive.

This difficulty was overcome in the design invented by White in 1890, called the solid back type (Fig. 9). Millions of these are used today in the ordinary desk-stand instrument. In this, carbon granules

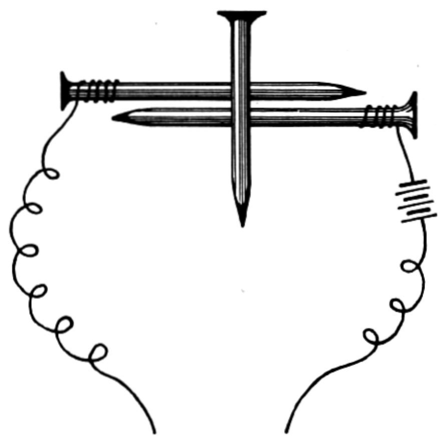

Fig. 5—Nail contacts used by Professor Hughes in 1878 to demonstrate their microphonic properties.

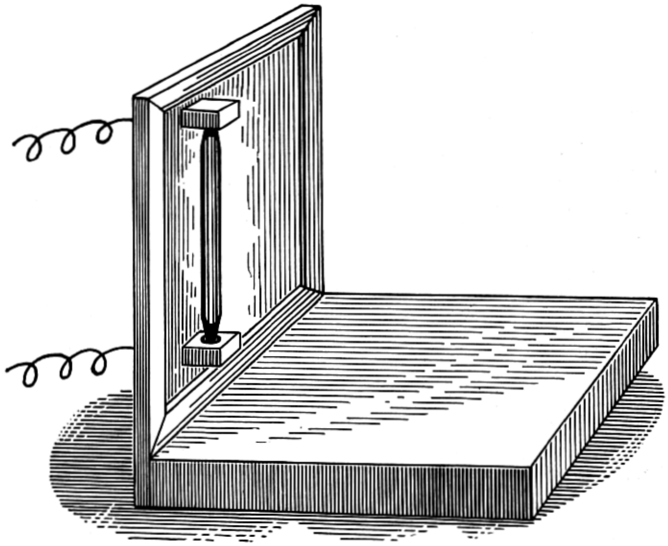

Fig. 6—Carbon pencil type microphone, mounted on a sounding board, demonstrated by Hughes in 1878.

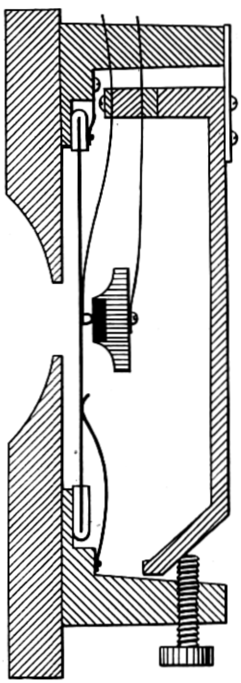

Fig. 7—The Blake transmitter using a platinum contact pressed against a carbon block.

are compressed between two polished carbon electrodes which are immersed in the granular mass in such a way that the particles have more freedom of movement than in the Hunnings instrument. This relieves excess pressure without undue packing.

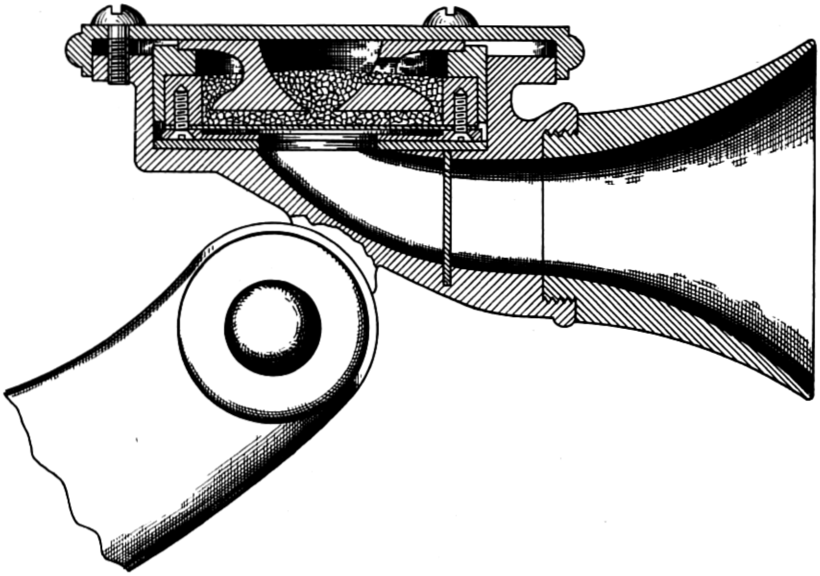

Fig. 8—Commercial model of the early Hunnings transmitter in which granular material was first used.

In Fig. 10 we have a cross-sectional view of a modern handset transmitter. This instrument, which is designed to operate in a wide variety of positions, follows the Hunnings' type in that the granular mass rests against the diaphragm but it differs from it in that the diaphragm does not act as an electrode. Both electrodes, separated by an insulating barrier, form part of the containing walls of the cell holding the carbon. This is the type which has recently been studied in detail and of which a two dimensional model is shown in Fig. 26.

The carbon used in these instruments is made by a heat treatment of anthracite coal. The particles are about 0.01 inch in size and when magnified they look just like lumps of coal taken from the domestic pile (Fig. 11).

Speculations of the Early Inventors

Part of the difficulty in elucidating the microphonic action of the "loose contact" arises because so many effects can be observed or are associated with the action that it is hard to determine which of them is essential. It is therefore not surprising that there was great diversity of opinion amongst the early inventors.

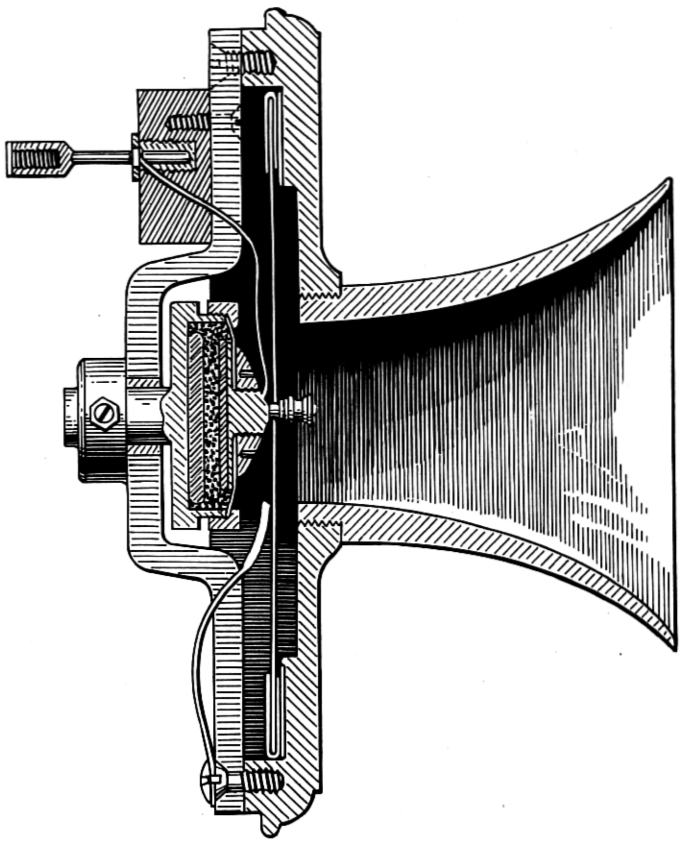

Fig. 9—The solid back transmitter invented by White in 1890.

For instance, experiment shows that contacts tend to move apart when in the act of transmitting sound. This led many, amongst them Berliner, to hold the view that an air film is necessary for microphonic action, that the current somehow passes through the film, and that the variation of the current is due to the variation of the thickness of the film. This view, however, was partly discredited by experiments showing that the moving apart was probably due to a heating of the contact through the passage of current and hence that it is not a necessary accompaniment of microphonic action.

Again, when one listens through a receiver placed in a circuit containing a "loose contact," noises are heard, especially when the voltage across the contact or microphone is large. These noises are irregular like frying or crackling. Also, if a contact be viewed under a microscope, bright spots are sometimes seen. These facts have led many to think that small arcs are always present and are responsible for microphonic action. Hughes was very much inclined to this view.

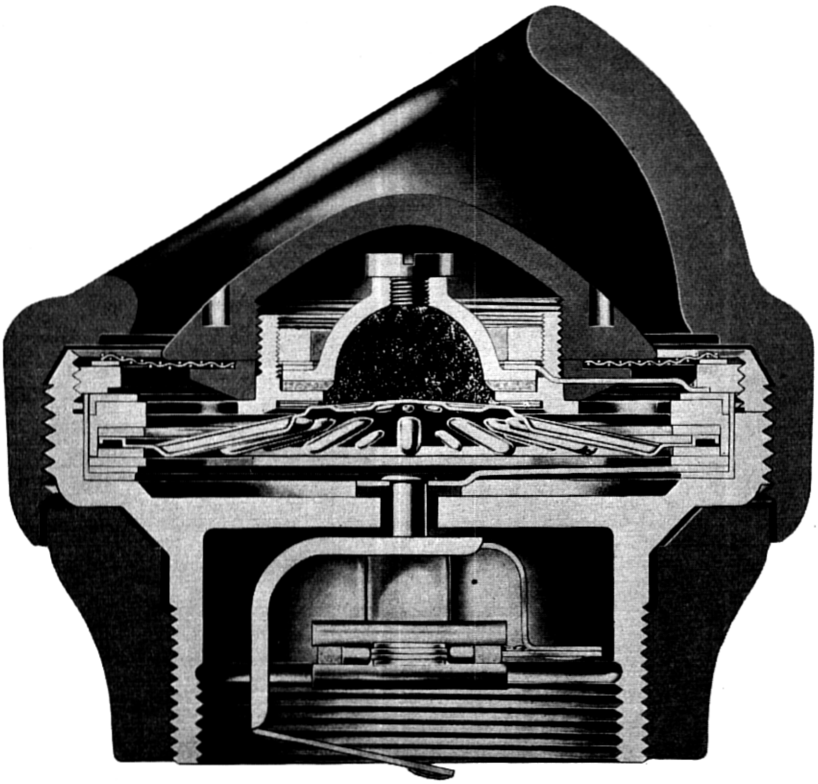

Fig. 10—Cross-section of the barrier type transmitter used in modern handset instruments.

There were reasons for supposing that the heating of the contact is a necessary factor in microphonic action. This point of view was supported by Preece, who wrote in 1893, "Indeed there are many phenomena such as hissing and humming that are clearly due to what is known as the Trevelyan effect, that is, the motion set up by expansion and contraction of bodies which are subjected to variation in temperature. This at least tends to favor the heat hypothesis as does also the fact that with continuous use some transmitters become essentially warm."

Another view was that microphonic action arises from change in resistivity of the solid carbon resulting from strain. This view was held by Edison who doubtless believed it because of the success of his microphone which was designed with the object of applying pressure variation to a solid carbon block. It failed of general

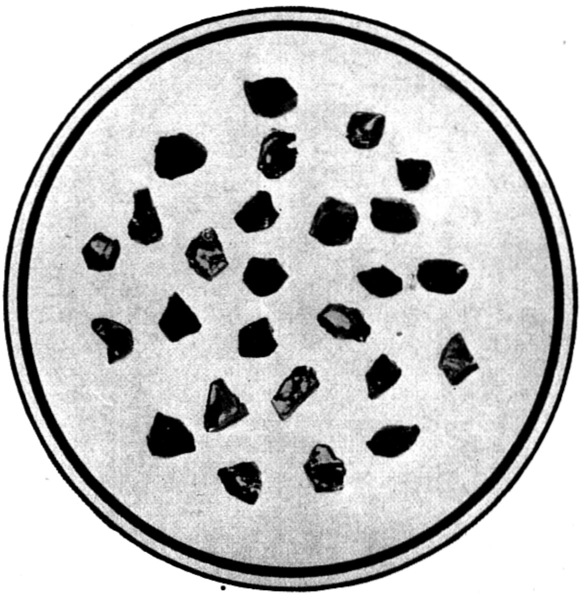

Fig. 11—Carbon granules made from anthracite coal (× 15).

acceptance because the effect of pressure on resistance, as shown by experiment, seemed definitely to be too small. It was generally considered that the Edison instrument was in fact a "loose contact" although Edison himself did not realize it.

Others of the early inventors considered the contact area to be the essential element—that is to say, the extent of surface or the number of molecules involved in intimate contact. As Professor Sylvanus Thompson expressed it in 1883, "An extremely minute motion of approach or recession may suffice to alter very greatly the number of molecules in contact. . . . Just as in a system of electric lamps in parallel arc the resistance of the system increases when the number of lamps is diminished and diminishes when the number of lamps connecting the parallel mains is increased, so it is with the molecules at the two surfaces of contact."

RECENT THEORIES

The first attempt at a quantitative theory of microphonic action was made by Professor P. O. Pedersen in 1916.[2] He assumed that microphonic action is due to the variation of the contact area arising from the elastic deformation of the contact material by pressure. Considering the case of two elastic conducting spheres brought into contact, Pedersen assumed that the resistance is made up of two parts; viz., (1) the resistance of a conducting film having a specific resistivity differing from bulk carbon and independent of pressure, and (2) the so-called "spreading resistance" or that which is caused by the concentration of the current flow within the region of the contact area and which would exist independently of any film.

This theory results in a quantitative expression [3] for the dependence of the contact resistance on the force holding the contacts together. Pedersen tested it by experiments on carbon spheres and found reasonable agreement over a wide range of force. However a very similar expression can be obtained without postulating the existence of the high resistance film. We have merely to suppose that contact does not take place over the whole contact area owing to surface roughness (the existence of which can be observed under a microscope, especially in the case of carbon).

Dr. F. Gray of Bell Telephone Laboratories worked out an expression [4] based on this assumption which was so nearly like Pedersen's that it was difficult to discriminate between them experimentally. He assumed both that the number of microscopic hills in electrical contact increases as the contact force is increased and that the resistance per hill varies in accordance with the theory of spreading resistance as assumed by Pedersen. His equation was found to fit experimental curves remarkably well for contact forces which are relatively larger than those holding the granules together in a microphone. In the range of smaller forces, however, marked departures from theory were found, the measured value of resistance decreasing too rapidly with an increase of force. Although these departures were believed to be due at least in part to a plastic deformation of the contact material, it appeared possible that other factors come into play and may even be dominant in this region of small contact forces.

For instance, it had been demonstrated that adsorbed films of air are capable of producing a marked increase in the resistance of granular carbon contacts. This revived the air film theory as a possibility under the condition of small contact forces.

[2] *The Electrician*, Jan. 28–Feb. 4, 1916.

[3] $R = AF^{-2/3} + BF^{-1/3}$.

[4] $R = AF^{-7/9} + BF^{-1/3}$ (*Phys. Rev.*, **36**, 375, 1930).

Again there is a marked decrease in the resistance of granular carbon contacts with increase in voltage which had not been satisfactorily explained. This fact suggested amongst other possibilities that the conduction process may involve the passage of electrons across gaps of molecular dimensions in the manner of a cold point discharge. Field gradients of sufficient magnitude to extract electrons from a solid must exist in these gaps with only a fraction of a volt across the contacts. If this is the main process by which current passes between contacts, microphonic action might well be associated with a variation of the gap dimensions under strain.

Again recent work on the theoretical strength of solids had led to experimental results showing that under certain conditions solids may, without fracture, be subjected to strains greatly exceeding those heretofore obtained. This suggested the possibility that the microphonic effect of contacts might after all be associated with the straining of small junctions welded under pressure and current.

In view of the speculative nature of the situation it was clear that a new experimental attack on the problem was necessary. We have been making such an attack during the last few years and I now turn attention to some of the experimental results and the main conclusions to be drawn from them.

Recent Experimental Work

Statement of the Problem

Since the essential element in the carbon microphone is the so-called "loose contact," the first and most fundamental step toward the understanding of the physics of microphones is the solution of the problem of the "loose contact" when in its sensitive or microphonic state.

Measurements on microphones such as the handset have enabled us to specify pretty accurately the conditions under which any two granules within the structure operate when the microphone is transmitting speech or sound.

In addition to the voltage, which is limited to one volt per contact, these conditions may be stated briefly either in terms of contact forces or in terms of movements between centres of granules. When you realize how small these are—particularly the movements between centres of granules—you will, I think, not be surprised that the solution of the problem of the "loose contact" has been so long delayed.

For the condition of reasonably loud speech the diaphragm motion is about

$$1 \times 10^{-5} \text{ cm.},$$

which is just on the limit of resolution of the highest-power microscopes. It follows from a consideration of the number of granules in series that the movement between centres of granules would not be greater than 1/10th of this, viz.,

$$1 \times 10^{-6} \text{ cm.,}$$

which is in the submicroscopic range. We must, therefore, be able to control and measure movements at least as small as 10^{-7} cm.; not an easy thing to do with a "loose contact."

The contact forces are on the average somewhat less than 10 dynes when the aggregate is in the unagitated state. In the presence of acoustic waves, variable forces of several dynes are superimposed on these fixed forces. The variable forces are smaller than the fixed forces, so that the granules will on the average remain in contact throughout any reversible cycle. We have reason to believe that 10 dynes is about the maximum force which is attained at any one contact during a stress cycle. We must therefore be able to control contact forces within the range 1 to 10 dynes.

Apparatus and technique have now been developed for studying single contacts within the prescribed range of forces and displacements, and significant measurements have been made which I will now endeavor to describe to you somewhat in detail.

Single Contact Studies

Figure 12 shows the construction of one of the contact tubes used in this study.

Its essential features are shown diagrammatically in Fig. 13. The contact pieces C_1 and C_2 are fastened respectively to a movable base M and to the lower end of a helical spring made of fused quartz. The base is supported from a fixed frame by two vertical platinum wires P and two stretched springs as shown. The lower contact piece is moved by heating or cooling the platinum wires through the passage of current. In this way the contacts may be made or broken and any desired contact force applied, the measure of the force being the compression of the helical spring. The temperature of the contact is varied by surrounding the contact region with a metal cylinder S which may be heated by means of radiation from a coil of platinum wire H, the temperature within the cylinder being measured by means of a thermocouple placed near the contacts.

In practice the upper contact piece consists of a single granule fastened to the end of a platinum wire and the lower contact piece consists of a number of granules attached to a horizontal metal plate;

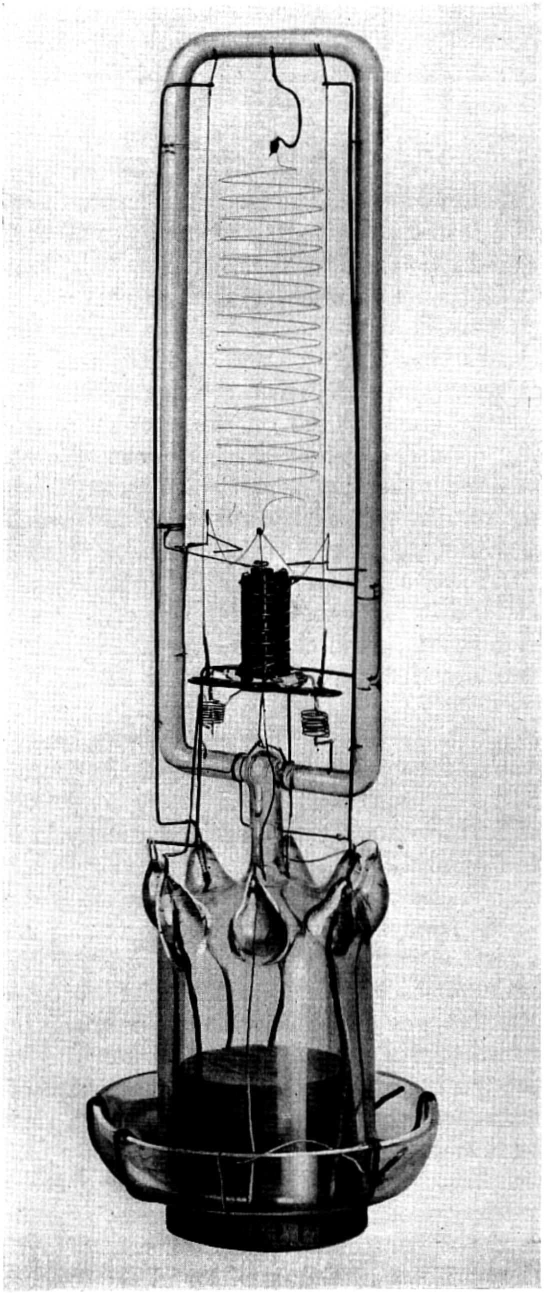

Fig. 12—Device for controlling force and temperature used in the study of single contacts.

in this way a variety of contacts can be studied with the same tube. A small hole in the metal cylinder permits of direct observation of the contacts during measurement. Figure 14 shows how the apparatus

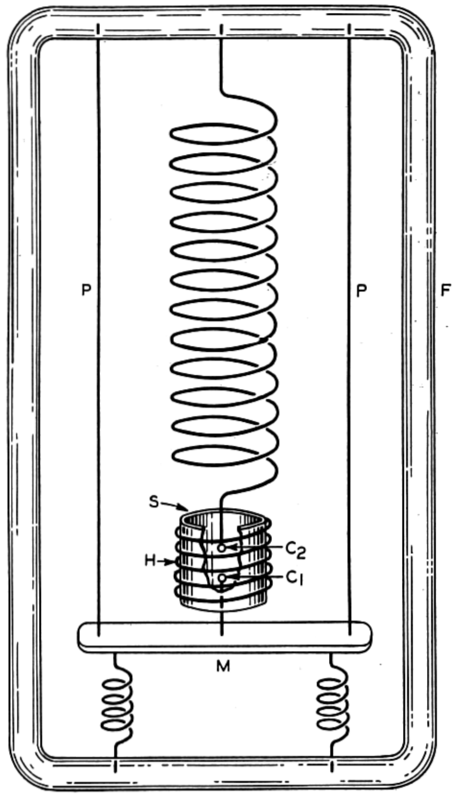

Fig. 13—Diagrammatic view of single contact device shown in Fig. 12.

was mounted in an iron cylinder on a damped suspension to protect it from acoustical and mechanical disturbance. The two microscopes were used to observe the compression of the silica spring.

We first studied the effect of voltage and temperature on contacts held together with constant forces. Reversible characteristics could in all cases be obtained for voltages up to 1 volt and for temperatures up to about 80° C.

Typical characteristics are shown on Fig. 15 in which the contact forces were of the order of 1 dyne. On the left are plotted the resistance-voltage characteristics and on the right the resistance-temperature characteristics. All of the variables are plotted for convenience on logarithmic scales.

The curves I, II and III illustrate the fact that Ohm's law is found to hold for all contacts up to about 0.1 volt and that above these values the contact resistance decreases with increase of voltage.

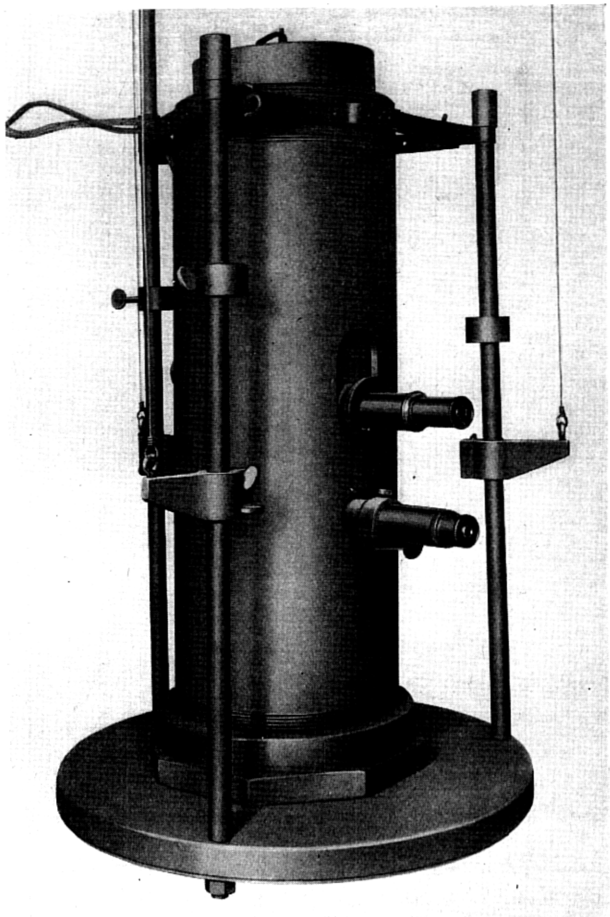

Fig. 14—The single contact device is mounted in a heavy container on a spring suspension to minimize acoustic and mechanical disturbance.

The fractional decrease in resistance with voltage above 0.1 volt is independent of the contact resistance and whether or not the measurements are made in air or vacuum.

In curves I', II' and III' we have changed the voltage scale of the curves I, II and III to a temperature scale in accordance with the relation,

$$T = T_0 + 40V^2.$$

This relation has a theoretical basis in the Joule heating of the contacts due to the passage of current and contains the assumption of a value of Wiedemann Franz ratios characteristic of solid carbon.[5]

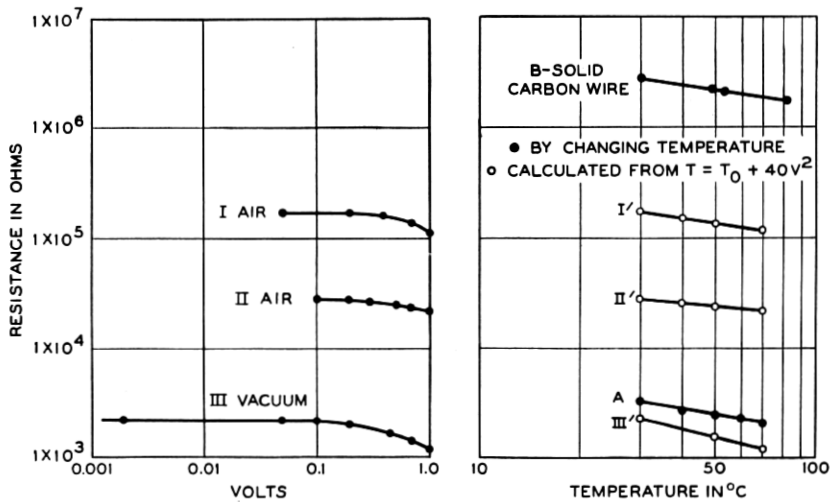

Fig. 15—Characteristics showing the effect of voltage and temperature on contact resistance.

These curves have substantially the same slope as A, which is a characteristic measured by heating a contact in the furnace, the contact voltage being sufficiently small to avoid appreciable heating of the contact due to this cause, and also with B, which was obtained with a solid carbon wire produced in a manner to simulate closely microphone carbon. We are able to conclude from measurements such as these that the nature of the conducting portions of contacts is that of solid carbon both for air and vacuum and that the departures from Ohm's law—at least up to 1 volt—are due to the Joule heating of the contacts.

From measurements similar to these in which we show that the admission of air has no effect on the temperature coefficient of resistance—although it produces a marked increase in the resistance at any particular temperature—we are also able to conclude that the presence of adsorbed air does not alter the nature of the conducting portions of the contacts but merely limits their areas.

[5] This theory, based on earlier work of Kohlrausch, was worked out in useful form independently in Bell Telephone Laboratories (unpublished work) and by R. Holm (*Zeit. Tech. Phys.*, **3**, 1922). It gives the approximate relation, const. $\frac{V^2}{K_0/\sigma_0}$, as the increase in temperature above room temperature, V being the contact voltage, and K_0/σ_0 the Wiedemann Franz ratio for the contact material.

Turning now to the effect of contact force on contact resistance: we see (Fig. 16) that large and approximately reversible resistance changes are produced as the force is varied repeatedly between fixed limits. This shows that the effect is in the main elastic, though the

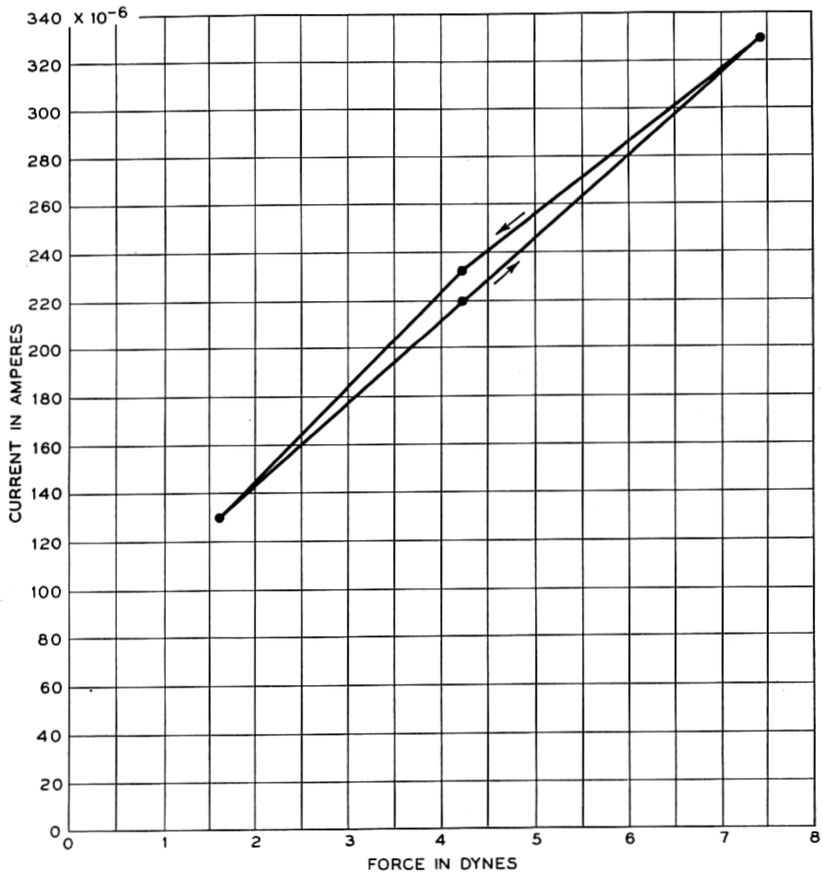

Fig. 16—Typical current-force cycle obtained with a single contact.

existence of a narrow loop indicates a small plastic or irreversible movement as a secondary effect.

We have thus established that the current is conducted through solid carbon and that the deformations are mainly elastic. These facts give strong support to the "elastic theory" of "loose contacts," i.e., the hypothesis that the change of resistance takes place because of a change in contact area under pressure. An extensive study of the resistance-force characteristics gave results which could not be simply interpreted (just as Gray had found) and, because of the possibility that unknown cohesional or frictional forces were involved, the work was extended by a study of resistance-displacement characteristics. Through a comparison of the two sets of data we were led to the conclusions that the stress-strain characteristics are not so simple as those assumed in Pedersen's or Gray's analysis and, therefore, that a study of the elastic behavior of contacts offered the most promising line of attack on the problem.

Figure 17 shows the mechanical system developed for this purpose. With it known forces can be applied to a contact element and at the same time its movement can be measured.

The contact is made between a carbon granule and a polished carbon plate, the granule being attached to the end of a rod R suspended by springs S from a fixed frame and the plate being attached to the end of a micrometer screw M_2 capable of giving to it a translational motion without rotation.

The force is applied to the granule electrostatically by means of voltage applied between the condenser plates C_2, one of which is attached to the rod R and the other to the micrometer screw. This is in principle the attracted disc electrometer of Kelvin and it is capable of applying forces up to 15 dynes without using voltages greater than 200.

The motion of the granule with respect to the carbon plate is measured electrically through the variation of capacity of the condenser C_1, of which one plate is attached to the other end of the rod R. C_1 forms part of an oscillating circuit of natural frequency n_0 (about 2000 kc.) which is coupled to a wave-meter circuit adjusted for oscillation at a frequency n_1 slightly different from n_0. Changes in the frequency arising from the changes in capacity C_1 alter the energy picked up by the wave-meter circuit and this energy, which is recorded by means of a galvanometer, serves as a measure of the change of capacity or motion of the rod R. With this arrangement it is possible to measure motions as small as 1×10^{-7} cm. and under the best conditions as small as 1×10^{-8} cm. It is necessary to have good damping, which is obtained by means of immersing the drum D in polymerized castor oil. The accessory spring S_2 is used merely for calibrating purposes.

Figure 18 shows the appearance of the apparatus as set up for measurement. The condenser is contained in the lower housing at the left, the wave-meter in the upper housing. The whole apparatus including the galvanometer is supported on a delicate spring suspension within a second large lead container, the frame of which just appears at the edge of the photograph and which is also supported by springs.

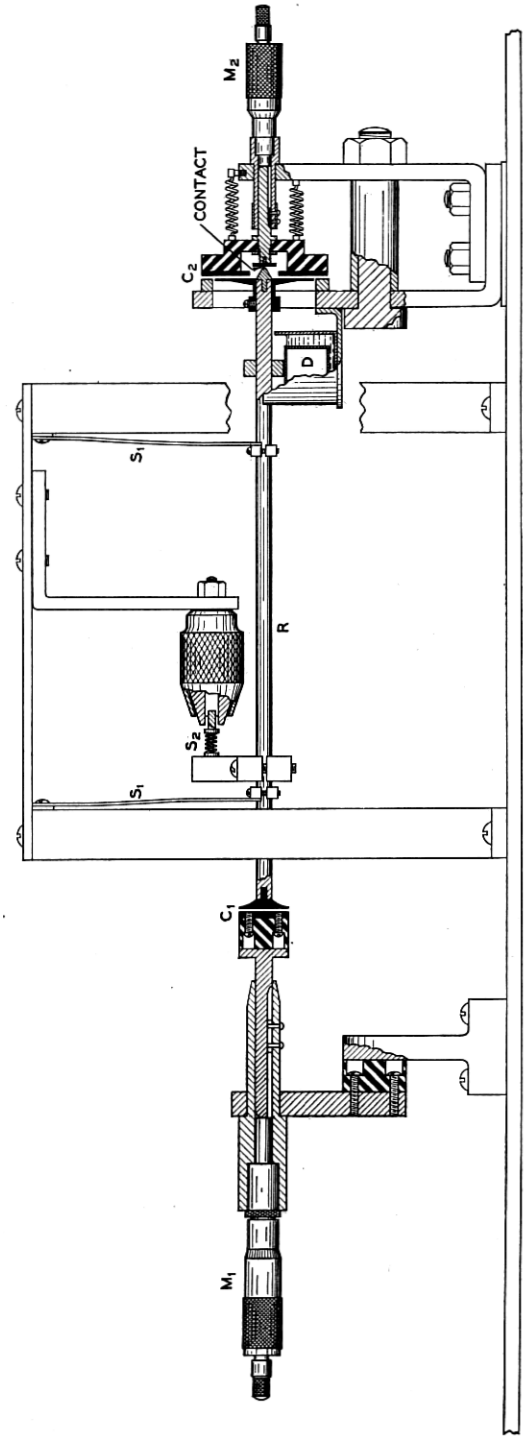

Fig. 17—Diagrammatic view of mechanical system used in the study of single contacts.

Figure 19 shows the appearance of the complete setup with the cover on the outside container. This begins to compete with cosmic ray apparatus from the point of view of the amount of lead involved, the outer container weighing about 600 lbs. Port-holes—one of

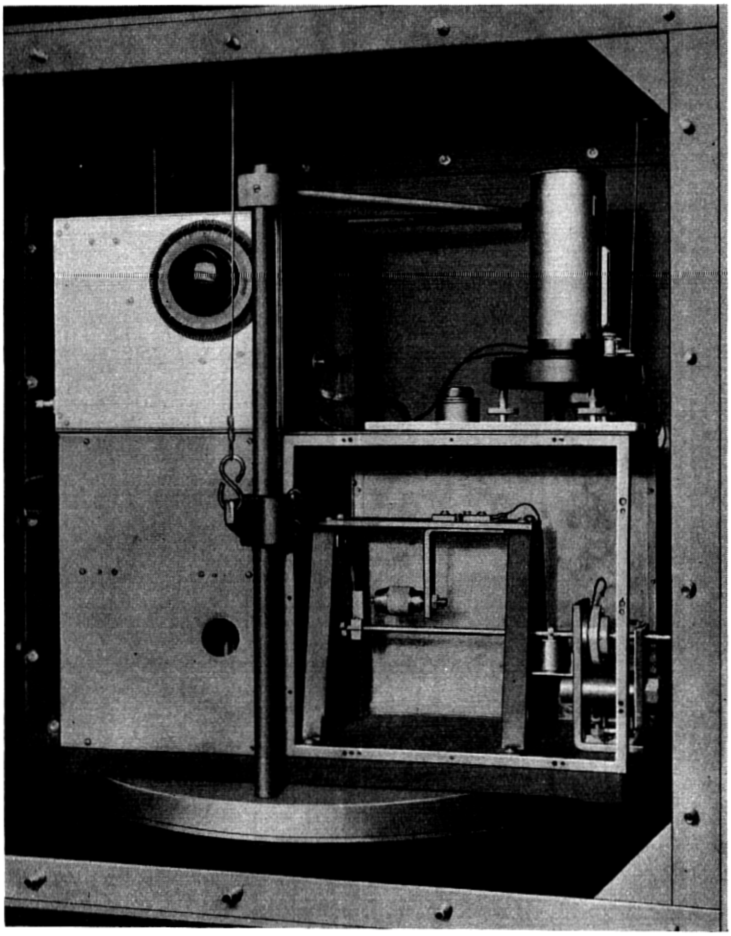

Fig. 18—Mechanical system and associated electrical apparatus as set up for single contact study.

which appears on the near end of the box—permit adjustments to be made on the apparatus within, thus eliminating the necessity for removing the large outer cover which, as you may surmise from the number of handles, requires the combined efforts of two men to remove it. All of this protection is, of course, to shield the apparatus from mechanical vibrations and acoustic disturbances.

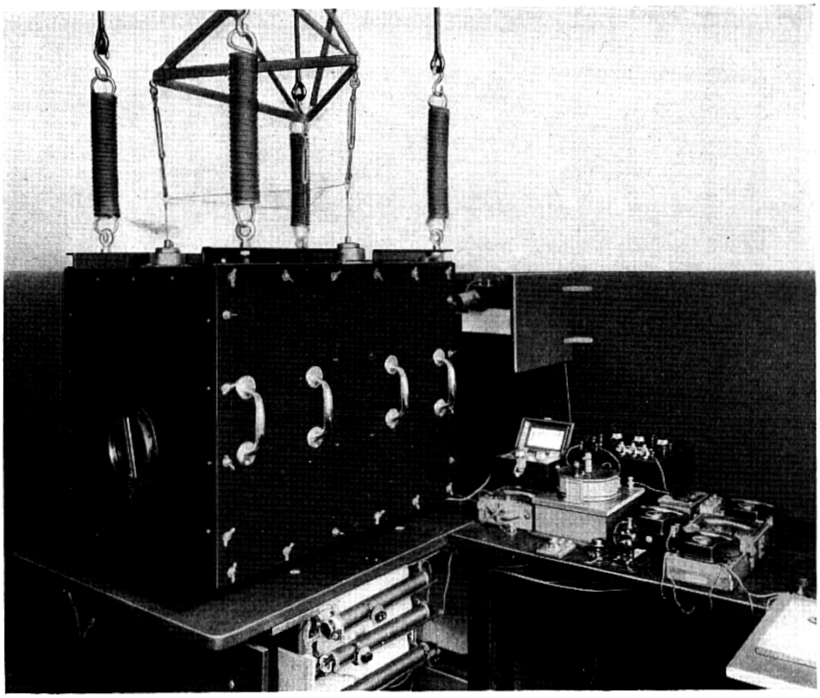

Fig. 19—Exterior view of complete experimental arrangement.

With this apparatus we investigated the variations in displacement and resistance when the forces are varied cyclically between fixed limits. Measurements on a large number of contacts are summarized in curves, Figs. 20 and 21. The cyclic characteristics, though somewhat irregular and having the form of narrow loops, approximate straight lines when the variables are plotted on logarithmic scales. Only one complete characteristic is shown in each set of curves, other typical measurements being represented by dotted straight lines joining the end points of their respective cycles. The full line in each figure represents the cycle of a typical contact, obtained by averaging, over the range in which the difference between the maximum and minimum force limits or maximum and minimum displacement limits is relatively large, in which case the slope is apparently constant.

If we let N'' and N represent the slopes of the typical force-displacement and resistance-force characteristics and if F, D and R be the contact force, the contact displacement and the contact resistance,

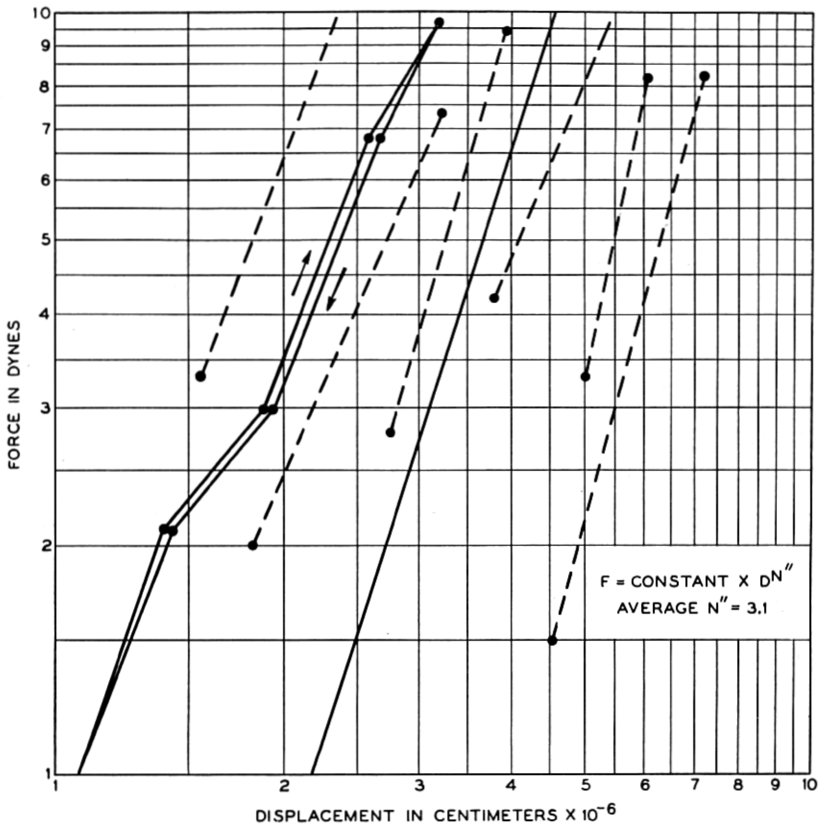

Fig. 20—Typical force-displacement characteristics of carbon granules pressed against a polished carbon plate.

respectively, we may express our results by the approximate relations:

$$F = \text{const.} \cdot D^{N''}, \tag{1}$$

$$R = \text{const.} \cdot F^{-N}. \tag{2}$$

The values N'' and N are not, however, independent of the force or displacement limits when these limits are relatively small. In Fig. 22 we have plotted values of N'' and N as functions of the difference between the maximum and minimum displacement (ΔD). We see that for relatively large values of ΔD, N'' and N approach the limiting values 3.1 and 0.47, respectively, but for smaller values of ΔD, N''

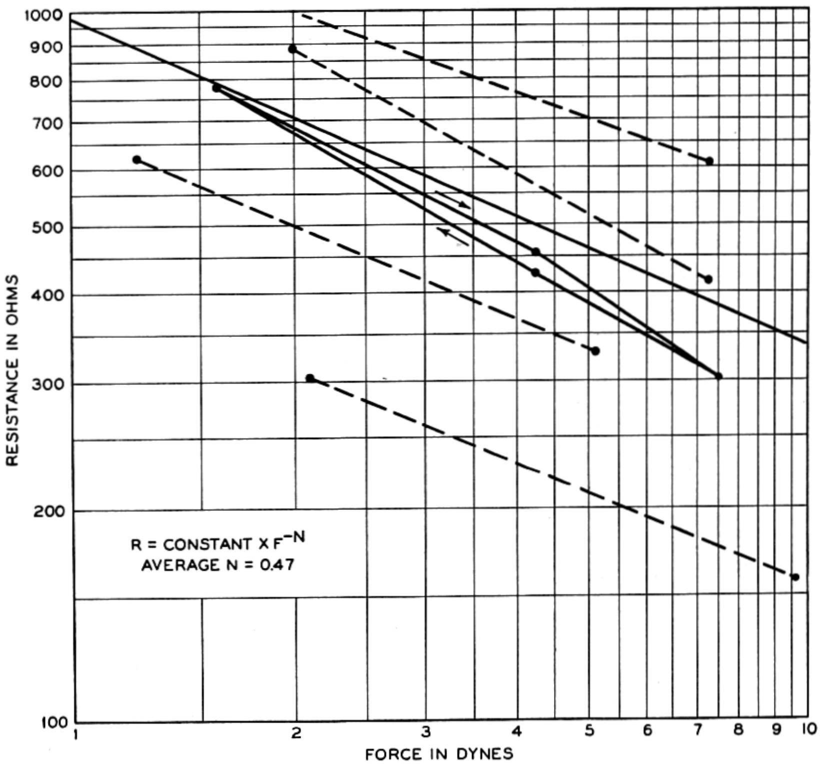

Fig. 21—Typical resistance-force characteristics of carbon granules pressed against a polished carbon plate.

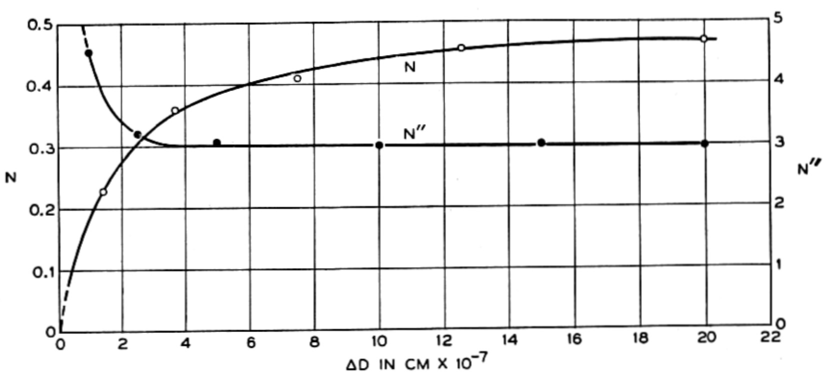

Fig. 22—Effect of the extent of contact motion (ΔD) on N and N''. (Average values.)

becomes greater than and N less than its limiting value. The limiting value of N'' is greater than that which would be obtained through the contact of hemispherical surfaces and represents a more rapid stiffening of the contact with compression.

We will first give our attention to the limiting value of N''.

A consideration of the nature of contact surfaces as revealed by the microscope furnished the clue to the interpretation of our results. A typical surface is shown in the photomicrograph (Fig. 23). Evi-

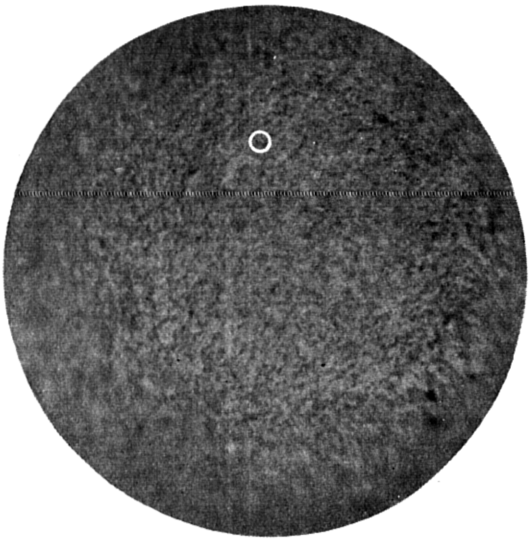

Fig. 23—Photomicrograph of the surface of a carbon granule ($\times$ 2400).

dently it is very hilly, the hills being much the same size and height. The magnification ($\times$ 2400) is such that the small white circle has a diameter of 8×10^{-5} cm. and it is clear that the circle encloses several hills.

From the theory of elasticity we may deduce that if two hemispherical hills of carbon having a radius of the order 1×10^{-5} cm. are brought together with forces of the order of 1 dyne the maximum stresses will probably not exceed the elastic limit of carbon and hence that the hills will deform elastically. The motion involved in such a deformation will be of the order of 1×10^{-6} cm. and if other hills are encountered, as is most probable with such a movement, the stresses will be shared and hence the stress per hill reduced. According to this view forces larger than one dyne can be applied without exceeding the elastic limit merely by virtue of the distribution of the hills which will come in to share the stresses. Furthermore, such a contact will stiffen up more rapidly with compressional displacement than will a contact made on a single hill. This concept of a loose contact, therefore, seemed to offer possibilities in the way of an adequate explanation of the experimental results.

At first the problem seemed too complex for mathematical analysis and a study of the elastic behavior of contact surfaces having various arrangements of little hemispherical hills was made with the aid of large scale rubber models. Quarter inch rubber balls were cut in half for this purpose and arranged on bases of suitable material and shape.

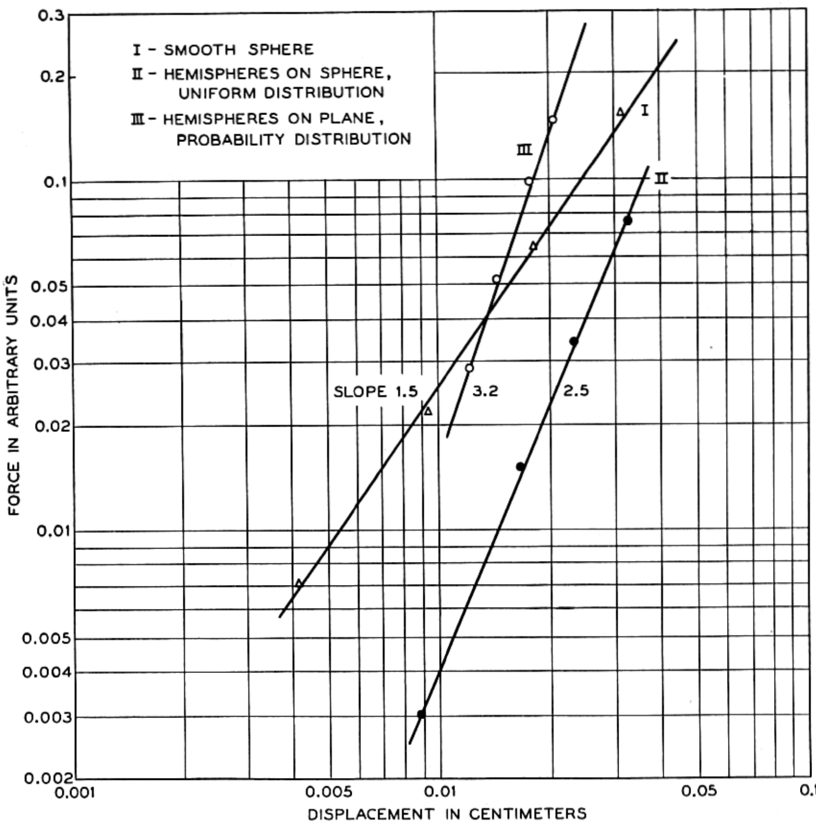

Fig. 24—Stress-strain characteristics obtained with contact surfaces made of rubber.

In Fig. 24 we have plotted the force-displacement characteristics of three different surfaces: *I*, that of a single smooth hemisphere; *II*, that of small hemispheres of equal height evenly distributed on a portion of a large 32 inch sphere made also with rubber; and *III*, that of hemispherical surfaces of random height fastened to a flat plate, about 100 hemispheres being used.

We see from the slopes of these curves that the model made with hills of random height on a flat plate behaves most like the actual contacts, the slopes of the corresponding curves being 3.2 and 3.1, respectively. This arrangement is also the one which most nearly represents the carbon surfaces as viewed under the microscope. Here the hills have various heights and the radius of the underlying base (0.015 cm.) is so much larger (1000 fold) than that of the average hill that within the region of the contact area the surface of the former may be regarded as plane.

The slope of curve *I* is in accord with a formula derived from the theory of elasticity by Hertz connecting the force F pressing together two elastic spheres and the movement D between the centres of the spheres:

$$F = \text{const. } D^{3/2}. \tag{3}$$

The constant includes such factors as the elastic moduli of the contact materials and the radii of the spheres and need not concern us here. The case of a sphere pressed against a flat plate, as in our experiments, is a particular case of this general equation, the constant only being affected.[6]

The slopes of curves *II* and *III* are also in accord with theory, as we shall see, when one makes the simple assumption that the elastic deformation is confined to such a small region near the contact in each hill that the underlying base is not appreciably deformed. This assumption was tested in the case of the model having the spherical distribution of hemispheres by changing the stiffness of the rubber used in the underlying sphere. No effect was produced on the stress-strain characteristic (curve *II*). We may therefore consider that the elastic reactions produced in each hill are independent of each other and that the base is not deformed, so that with a given distribution of hills it becomes a simple matter to calculate their combined effect over a given compressional range. We may represent the conditions essential for our calculation by the diagram, Fig. 25, in which A represents the plane surface of the smooth contact element just making contact with the highest hill of the rough contact element. Under compression, A may be considered as moving in the direction of its normal x, compressing B and, with increasing motion, coming into

[6] Formula (3) is known to hold accurately for values of D not greater than about 1 per cent. of the radius of the sphere (J. P. Andrews, *Phys. Soc. Proc.*, Vol. 42, No. 236). This condition is fulfilled in the case of curve *I* but D is as great as 10 per cent. of the radius in the case of a few of the hills involved in the maximum compression shown in curves *II* and *III* (Fig. 24).

contact with other hills C and compressing them according to equation (3). The position of C is conveniently defined by its distance X from the plane A.

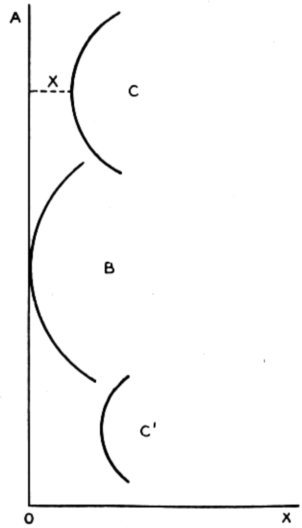

Fig. 25—Schematic representation of a rough surface used in mathematical analysis.

Any continuous distribution of hill positions, typified by C, which would be encountered through a small compressional movement, may be approximately represented by the expression,

$$N_x = \text{const. } x^n, \tag{4}$$

where N_x is defined as the number which multiplied by dx gives the number of hills coming into contact with the plane when it moves from x to $x + dx$. The exponent n is a constant which for convenience we may call the distribution constant.

For a total compression D the $N_x dx$ hills will be compressed an amount $D - x$, and hence the total force of reaction F is given by

$$F = \text{const.} \int_0^D x^n (D - x)^{3/2} dx,$$

which integrates to the form,

$$F = \text{const. } D^{n+5/2} = \text{const. } D^{N''}. \tag{5}$$

The constant here includes a summation of the individual constants of equation (3). It is clear that if the hills have different radii the constant only will be affected, so that equation (5) may be regarded as general in this respect.

For the case of uniform hills distributed on the surface of a sphere it may be shown that equal numbers of hills will be added for equal increments in x, in which case $N_x = \text{const.}$[7] From this it follows that $n = 0$ and $N'' = 2.5$ in agreement with the measured value, curve *II*.[8] For $N'' = 3.2$ as obtained with the hemispheres of random height on a plane, curve *III*, n would have the value 0.7. The corresponding distribution function N_x would approximate to that of the portion of an ordinary error curve near its maximum. A rough determination of the distribution of heights amongst the small rubber hemispheres showed in fact that they approximated closely to an error curve and that the displacement range covered that portion of the curve near the most probable height.

It would appear from this analysis that the elastic behavior of our carbon contacts under conditions of relatively large strain is adequately explained on the very simple assumption that the hills which we observe under the microscope have a random distribution of heights and behave like smooth spherical surfaces. We have, however, still to account for the hysteresis and the large values of N'' corresponding to small values of ΔD as well as the values of N (Fig. 22).

It is unlikely that the hills which we observe under the microscope are submicroscopically smooth, in which case we would expect a small plastic movement in these secondary hills arising from overstrain. We have direct evidence for this in the fact that contacts once established—even without the passage of current—require relatively small but finite forces to break them. Such junctions within the contact region could well account for hysteresis and a stiffening up of the contact in the region of small strains. Furthermore it is to be expected that they might affect the resistance behavior to a much greater extent than the elastic, and over a wider range of strain, since the junctions—though too weak to affect appreciably the contact stiffness—might well carry a relatively large proportion of current; in which case the value of N would be smaller than that calculated on the assumption of smooth spherical surfaces.

We will now derive an expression relating resistance and force for the type of contact considered in the derivation of equation (5), assuming smooth hills.

Classical theory [9] gives the following formula for the conductance

[7] This argument rests on the fact of geometry that if A is the area of contact between a sphere of radius r and a plane, $dA/dx = 2\pi r$.

[8] This agreement between theory and experiment shows that the compression of some of the hills by an amount in excess of 1 per cent. of their radii has not affected the applicability of equation (3) to our problem.

[9] Riemann Weber.

It is here assumed that the mechanical and electrical areas of contact are coincident, which according to the ideas of wave mechanics may not be the case.

$1/r$ of the contact formed by compressing, by an amount D, a single smooth conducting sphere against a flat conducting plate,

$$\frac{1}{r} = \text{const. } D^{1/2}. \tag{6}$$

It appears reasonable to assume that the hills which come into contact with compression act independently of each other as regards conduction. The conductances may therefore be added and we may write for the total conductance $(1/R)$ produced by a compression D involving many hills:

$$\frac{1}{R} = \text{const.} \int_0^D x^n (D - x)^{1/2} dx,$$

which integrates to the form,

$$\frac{1}{R} = \text{const. } D^{n+3/2},$$

which in combination with (5) gives

$$R = \text{const. } F^{\frac{2n+3}{2n+5}} = \text{const. } F^{-N}. \tag{7}$$

Using the value of n consistent with equation (5) through the measured value of N'', viz., $n = 0.6$, we get $N = 0.68$. The measured value of N (0.47) is, as we have surmised, too small though it is of the right order of magnitude.

We are, of course, investigating the factors which give rise to this discrepancy as they will play an important part in any complete theory of microphonic action, and we are extending our study to the behavior of granular aggregates in simple cells and microphone structures. We have shown that the value of N in a simple cell composed of parallel electrodes is quite consistent with our simple theory for single contacts, which therefore indicates that the behavior of an aggregate of contacts is determined by the behavior of the individual contact. Furthermore, we have shown, through static measurements on the handset instrument, that the granular aggregate within this irregularly shaped structure behaves like the aggregate in a simple cell. We are therefore confident that the behavior of the microphone will be explained in terms of the behavior of the single contact.

The behavior of the two dimensional model of the handset microphone (Fig. 26) is most convincing in this connection. Although this model was set up originally to study the distribution of stresses in this type of structure it has proved most useful in other phases of our work. Quarter inch rubber balls represent the granular particles of

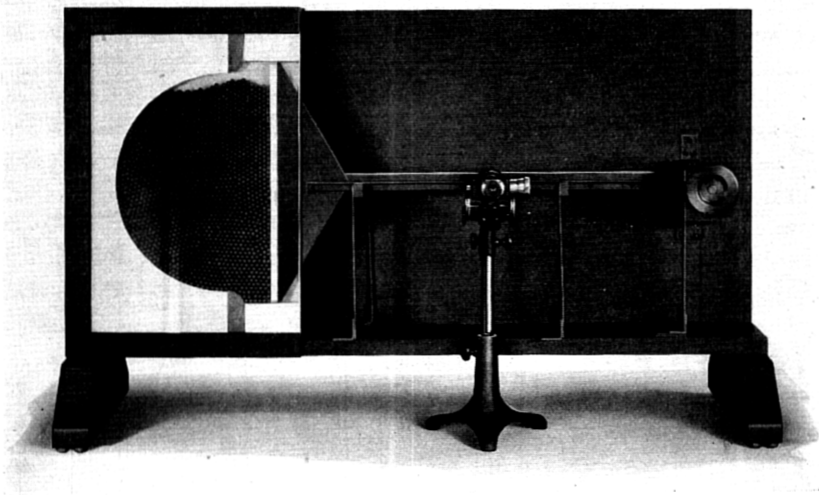

Fig. 26—Model of handset transmitter cell.

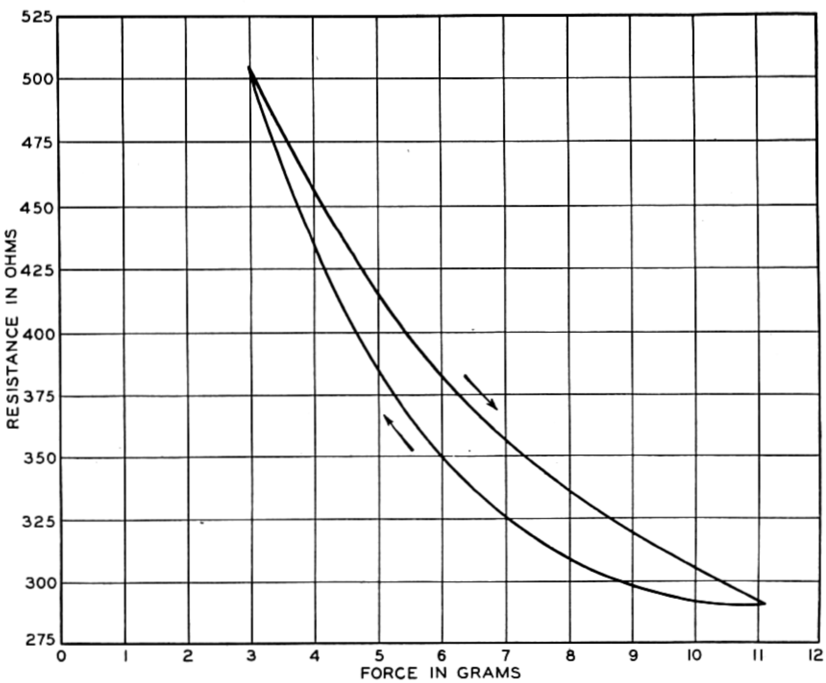

Fig. 27—Resistance-force cycle obtained with transmitter model.

the actual microphone and by coating these with a conducting layer of graphite and lacquer we are able to make them behave electrically as well as elastically in accordance with our simple theory. When placed in the model the aggregate is compressed cyclically by means of the piston which acts as a diaphragm, producing a change of resistance in the current path around the insulating barrier. The curves shown in Figs. 27 and 28 show typical resistance-force cycles, obtained with the model and the actual instrument under conditions wherein the reactive forces are mainly elastic. The similarity of these characteristics is striking. The existence of the loops indicates that the reactive forces are not entirely elastic and that the behavior is modified by friction, as in the case of single contacts.

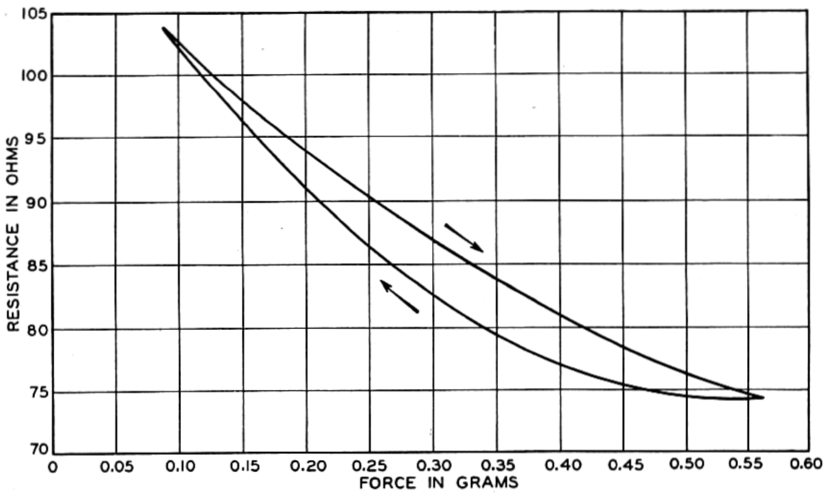

Fig. 28—Resistance-force cycle obtained with a standard transmitter.

In conclusion it seems fair to say that our experiments on "loose contacts" under conditions which are equivalent to those under which they operate in actual microphones have given a satisfactory picture of the essential nature of such contacts, and their mode of operation when strained, both from the elastic and the electrical point of view. The electrical current is carried through regions in intimate contact and changes in resistance under strain are due both to a variation in the number of microscopic hills which form the carbon surface and to area changes at the junctions of these hills arising from their elastic deformation in accordance with the well known laws of elasticity.