THE TELEPHONE

OUTLINES OF THE DEVELOPMENT OF TRANSMITTERS AND RECEIVERS

By the Same Author.

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THE TELEPHONE

OUTLINES OF THE DEVELOPMENT OF TRANSMITTERS AND RECEIVERS

BY

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PREFACE.

THIS little book is offered without apology. Its issue has been prompted by the fact that in no book which has come to my notice, on the same subject, is there a clear and connected explanation of the principles underlying the action and the design of telephone transmitters and receivers. I have avoided making a descriptive catalogue of instruments, and have endeavored to set forth the facts and principles in such a way that they will be easily and thoroughly understood. For this reason, those instruments only have been described which have demonstrated their importance by long service, or which seem to mark steps in the development of modern transmitters and receivers. A thorough grasp of these principles will make it easy to apply them to individual instruments.

Although written primarily for men engaged in practical telephone work, it was my intention that the book should serve also as the basis for a lecture course to students. In the most progressive technical schools of the present day, lecture courses are provided, at an advanced period, upon special branches of engineering. These lectures are given by specialists, and each series covers, so far as circumstances allow, the practice in that particular branch, as an immediate preparation of the student for contact with active professional work. A general comprehensive training in mathematics, science, and other engineering subjects is presupposed, and no attempt is made in these courses to supply such matter, which the student has usually acquired thoroughly at this stage of his education.

One special subject of this class is telephone engineering; and that subject must include, among other matters, substantially what is given in the following pages. Telephone lines and their properties, which also belong in such a course, are treated in a similar manner in a book which has been before the public for some years.

WILLIAM J. HOPKINS.

PHILADELPHIA, May, 1898.

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THE TELEPHONE.

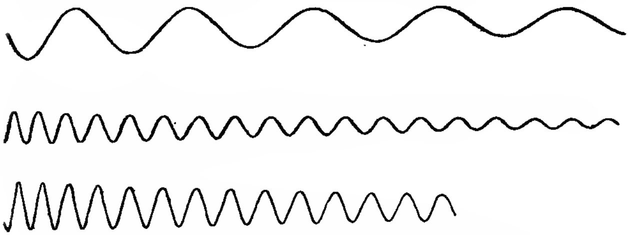
OUTLINES OF THE DEVELOPMENT OF TRANSMITTERS AND RECEIVERS.

CHAPTER I.

SOUND.

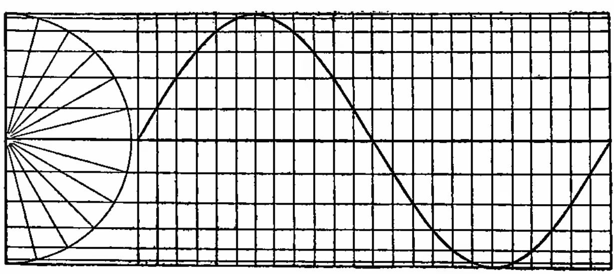
Any body which is emitting sound waves is in vibration, moving to and fro, either as a whole or in parts; and the motion of each particle, however complex, is exactly repeated at regular intervals. We may best examine the motion of sounding bodies by causing them to trace a curve, by a light style on smoked glass or by a pen upon paper moved with uniform speed in a direction perpendicular to the vibration. Such curves are not difficult to obtain, and a motion thus recorded we can examine at our leisure. Bodies which are actually giving out sound, however, vibrate so rapidly and through such a small distance that the curves they trace are not so easily examined as those traced by bodies which are vibrating too slowly to cause the sensation of sound, although the motion is of exactly the same character.

If a thin bar of spring brass or steel is firmly clamped at one end, and the free end pulled to one side and let go, a tracing point fixed to the free end



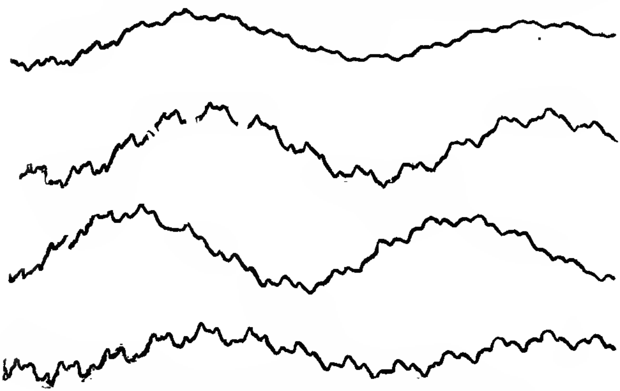
Simple Harmonic Curves Traced by a Vibrating Bar.

will describe the curve in the figure on paper moving at right angles with the vibration. Examination of this curve shows that the vibrating point is moving most rapidly as it passes its middle position in either direction. Its speed grows less and less after passing this position, until at the extremity of the swing the motion is reversed. The speed then increases up to the middle point, and this process is repeated until



Graphical Construction of the Harmonic Curve.

the vibration dies away. A curve of this general form is called a *Simple Harmonic Curve.* The exact proportions may be varied by changing the rate of motion of the paper or the amplitude of the vibration; but in every case the characteristics of the



Traces of a Vibrating Bar.

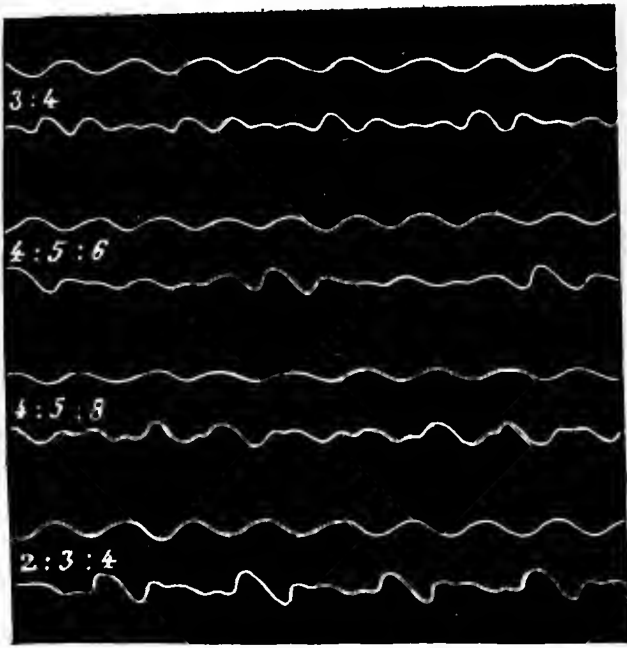
Three or more overtones superposed upon the fundamental.

motion are the same.* If the vibrations of such a body are within the range affecting our sense of hearing, the sound produced is round and full, of a quality which is easily recognized. Such simple

* If a small bright body is made to revolve uniformly in a circle and looked at from a point in the plane of the circle, it appears to be moving to and fro along the diameter of the circle. This apparent motion along the diameter is of the same character as the actual motion of a sounding body, and *harmonic motion*, as such vibration is called, may be studied mathematically by using this circle as a circle of reference and constructing the harmonic curve by compounding the vibration with uniform motion at right angles with it. The method of construction is indicated in the figure on page 2.

sounds are produced by tuning forks mounted upon resonating boxes and by organ pipes under some conditions. Simple sounds are, however, of very rare occurrence in nature.

If the vibrating bar described above is struck at some point near its support, the tracing point may be made to describe some of the curves shown on page 3.



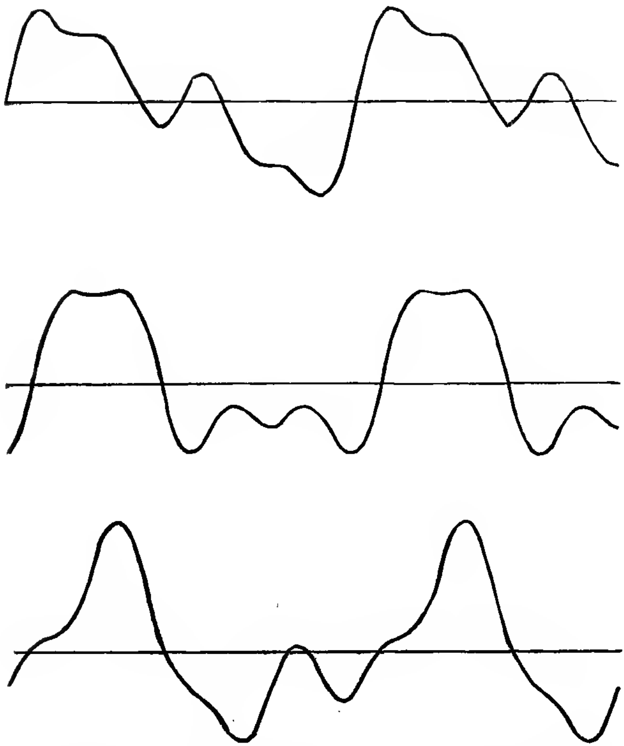
Enlarged Traces of the Phonautograph Membrane (Koenig).

The vibrations are caused by the simultaneous action of two or three simple sounds having the frequency ratios shown.
The simple harmonic curve beside the compound curve is, in each case, the trace due to a simple sound of 256 vibrations a second.

These curves correspond to sounds of less simple character than in the first case, and an analysis will show that each curve is made up of two or more simple vibrations occurring at the same time. Each vibration goes on independently, as though the others were not present, and the resultant curve might be determined, point by point, by adding together the distances from the middle position in one direction, and subtracting all those in the other direction. In a sounding body the vibration of longest period is called the *fundamental* tone, and the others, of shorter periods, are called *overtones*, partials, or harmonics. As these higher tones are not in all cases harmonic, in a musical sense, however, it will be best to call them overtones.

We can see from these graphical records that the motion of a vibrating body has three important characteristics. The distance to which it moves in either direction from the point of rest is called the *amplitude*, and this determines the loudness of the sound produced. The time taken to perform one complete vibration—from either end of the swing back to the same point again—is the *period*, and upon this depends the pitch. If one vibrating body has half the period of another, the sound produced by the first is an octave higher in pitch than that produced by the second. The third characteristic of the motion of a sounding body is the form of the curve traced. The form of the wave determines the quality of the sound, and this is evidently affected, not only by the relation of the periods and amplitudes of the components, but by their relative positions as well. That is, if two complex sounds are made up of the same component simple vibrations—the same both in period and in amplitude—and if in one sound all the component vibrations start at the same instant while in the other sound some of the component vibrations are half completed when the others begin, the form of the resultant wave is different in the two cases, and the quality of one of the sounds is consequently not the same as that of the other. The figure shows three curves in each of which the components are respectively of the same amplitude and period, but differently placed. The difference in the form of the curves is evident at a glance.

Quality of sound—character or *timbre*, as it is sometimes called—is difficult to define, but is generally understood. It is that by which different sounds of the same pitch are identified. A note of a given pitch is of quite a different quality when sounded upon a French horn, a piano, or a violin, and the tones of these instruments are characteristic and would not be confused. It is hardly correct to say that a simple sound has no quality, although the quality of all simple sounds is the same. Of all natural sounds, that of the human voice most abounds in overtones. As these overtones vary in number, in relative loudness, and in relative position, sounds



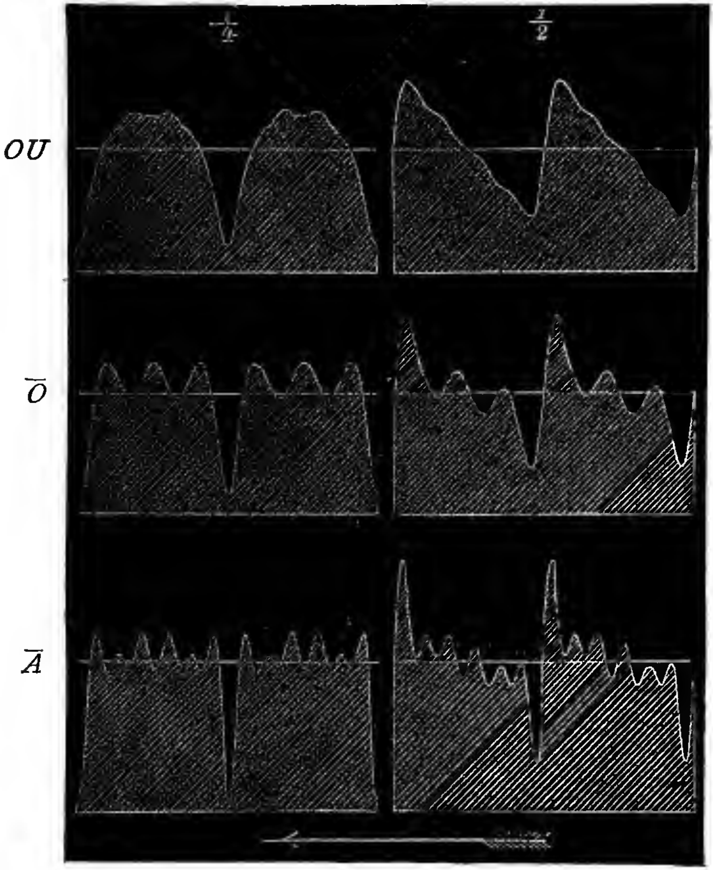
Three Curves made up of the same three component Vibrations.

The amplitudes and the periods of the components are respectively the same in each case, but the phase-relations are different.

are produced of almost infinite variety of quality, enabling us to discriminate, in a subtle way which defies mathematical analysis, between the voices of individuals, and to recognize the varying shades of thought and feeling which the voice expresses.

Articulate speech consists of a series of vowel sounds, broken and interrupted by consonants. The vowels have been found to consist of different arrangements of fundamental and overtones, and have even been produced artificially from known components. Consonants are produced by the contact of lips, tongue, teeth, or the roof of the mouth, some of them partaking slightly of the character of vowels. The vowels are produced at will, although without a definite knowledge of the mechanism, by a selective reinforcing of particular overtones from all the complex vibrations of the vocal cords and connecting membranes. This reinforcement is accomplished by modifying the shape and size of the cavities of the throat and head, including the mouth.

From these considerations it appears at once that the problem of transmitting speech to a distance electrically and reproducing, at the far end, the spoken sounds, was delicate and difficult. The air vibrations, which, if recorded, would give curves of the general character shown above, must be made to produce electrical undulations exactly similar, and these waves must be again transformed, by suitable mechanism, into air waves of the same form as those at the trans-



Curves resulting from the composition of the Simple Vibrations which make up the sounds of the vowels *ou*, *ō*, *ā* (Koenig).

With the phase-differences shown, the quality is altered, although the distinctive vowel sound is preserved.

mitting end. Any sort of selective action of the apparatus, therefore, at either end, whether in the blotting out of particular overtones, unequally diminishing the amplitude of the components or shifting them along with regard to each other and thus altering the wave form, would result in a change of quality and, to the extent to which any such action occurred, a failure to accomplish the desired end. The beautiful simplicity of the method finally adopted will appear in what follows.

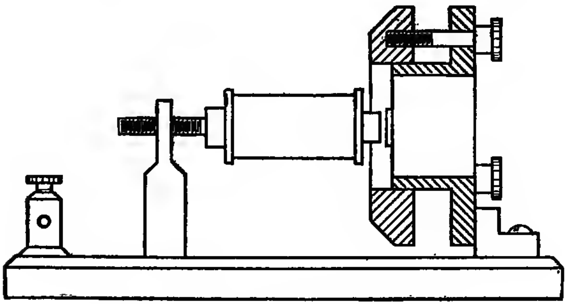
CHAPTER II.

HISTORICAL.

THE history of the telephone, at least so far as public knowledge and present use are directly concerned, began when Alexander Graham Bell and Elisha Gray filed in the Patent Office, on the same day, papers covering substantially similar instruments.

Bell's first instrument was too far from any form which has come into use to merit more than the briefest description here. Transmitter and receiver were similar, and of harplike character, depending for their action upon the principle of resonance. Strings or other vibrating members, of different lengths, each tuned to some definite pitch within the required range, were to be set into vibration, each by the particular component, in the sound to be transmitted, to which it would respond. The sound was thus analyzed mechanically, the components recombined electrically, mechanically analyzed by the receiver and the components again recombined in the air waves. The methods employed were not the same that appeared clearly intended in the later and better known instrument and upon which the present art of telephony rests.

This first instrument, as set forth in Bell's papers, was seen to be of too complicated design to come into extensive use on a commercial scale, and accordingly, before the patent was issued, the design was entirely changed and the resulting instrument was wonderfully simple. The transmitter is shown in the figure.

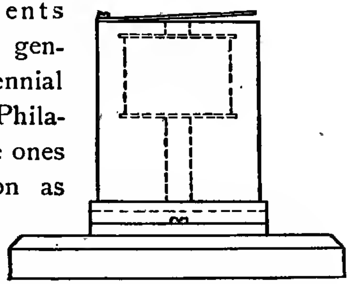


Bell's Centennial Double-Pole Transmitter.

An electro-magnet is mounted horizontally. In front of its free end is stretched a thin diaphragm of gold-beater's skin with a small piece of soft iron cemented upon its central portion, just opposite the end of the magnet core. Speaking into such an instrument sets up in the membrane vibrations following pretty closely the sound vibrations in the air. This motion of the soft iron armature gives rise to changes in the magnetic field and corresponding changes in the current flowing in the line. These current changes are transformed by the receiver into air vibrations reproducing the sound at the transmitting end more or less exactly, according to the efficiency of the instruments and the properties of the line.

The receiver first used by Bell was an electro-magnet, a single coil enclosed in a soft iron tube. The magnetic circuit was nearly, but not quite, closed by a disk screwed to the tube at one side and depending upon its own elasticity for maintaining vibrations under varying pull of the magnet.

These two instruments were first shown to the general public at the Centennial Exposition of 1876, at Philadelphia, and they are the ones which are looked upon as the progenitors of the modern instruments depending upon magnetic action. The design was soon modified, a permanent magnet with a small coil at one end substituted for the electro-magnet in the transmitter and a thin iron diaphragm for the membrane of gold-beater's skin. The first form of receiver was discarded and the modified transmitter used to perform the functions of both transmitter and receiver. Repeated, but slight, modifications in design soon brought this instrument into the form now in general use, known as the "magneto" telephone—in the telephone business

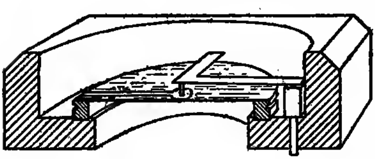


Bell's Centennial Tubular Receiver.

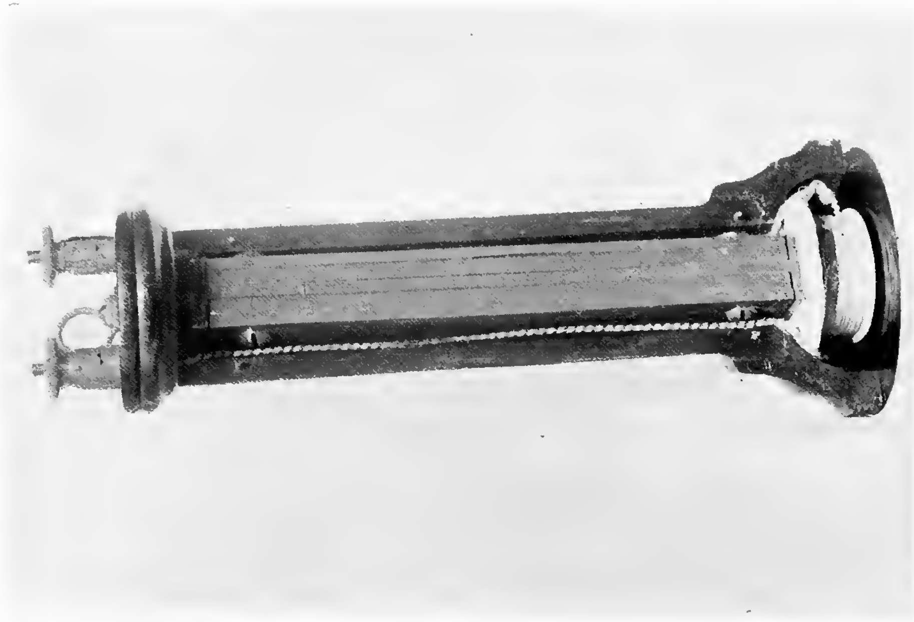
more customarily called "hand telephone"—which has been practically unchanged for years.

It was to be expected that a patent so broad in its claims and of such value would be the subject of extended litigation. The literature on the subject, in its legal aspect, is so voluminous that not even mention can be made here of the rivals whose claims have been, sooner or later, set aside by the courts. There is one invention, however, undoubtedly genuine, so far as it goes, which has been alleged as an anticipation of the invention of Bell, and which, at the time of its exploiting, found some strong adherents. This is the telephone of Philip Reis.

Reis's telephone was invented about 1861, and was intended to reproduce musical sounds. It consisted of a box, with an opening for a mouth-piece in one side, and a hole in the top, closed by a thin membrane. Any musical sound, therefore, entering the mouth-piece, would set the membrane into corresponding vibrations. To transmit these vibrations electrically to a distance, the instrument was arranged to break the circuit at every throw of the membrane. For this purpose, a light metallic arm rested loosely upon it, normally making contact, through a



Section through Working Parts of Reis's Transmitter.



HAND TELEPHONE.

Showing the arrangement of magnet, coil, and diaphragm. The cap, or mouthpiece, is not shown.

Hand Telephone, Complete.

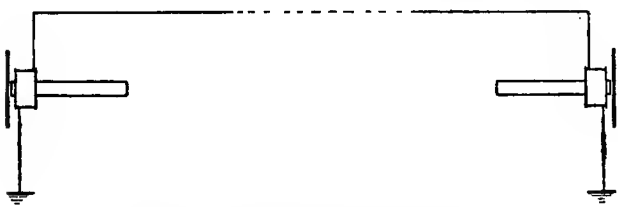
platinum point just over its centre, with a metal strip fastened to the diaphragm. When the diaphragm was set into vibration, therefore, this contact was broken at every excursion of the diaphragm, and an interrupted current sent over the line in accordance with the pitch of the sound. The receiver consisted of a long coil with an iron wire core, mounted upon a sounding-box. At every break of the current, a click was produced in the iron core, and the rapid succession of clicks blended into a musical tone of the same pitch as the sound at the transmitting end, although not necessarily resembling it in any other respect.

It was contended by the opponents of Bell's claims that by these instruments Reis had anticipated Bell in the transmission of speech; and in support of these contentions it was shown that a Reis telephone could transmit articulate sounds. The possibility of such transmission was granted by the Bell experts, but it was pointed out that the make and break feature of the Reis telephone was fundamental; that it was intended to transmit interrupted currents, and that the existence of varying continuous currents at the same time was incidental and unrecognized as of importance; that articulate speech could be reproduced and transmitted only by undulatory currents of electricity, as specified by Bell; and finally, that the transmission of speech by the Reis telephone was in spite of its characteristic action, and not because of it. Without touching upon the legal or the moral aspects of this question of priority and rights, we can see at once that this answer was in accordance with the fact. The Reis transmitter can be made, by proper adjustment, to act as a very fair microphone, so that speech can be transmitted *while the contact is unbroken.* The instant that contact is broken, however, the current is interrupted, and the transmission of speech is stopped. If, therefore, the interruption of the current was an intended feature of the operation of the instrument, Reis's telephone could not be held to be an anticipation of Bell's. The decision of the courts was along these lines.

CHAPTER III.

DEVELOPMENT OF TRANSMITTERS.

As constituted with the early Bell instruments, the telephone circuit was extremely simple. A magneto instrument, or "hand telephone," at each end of the line, was used for the double purpose of transmitter and receiver, and moved from mouth to ear as though it were the end of a speaking-tube.



Circuit for Magneto Telephones, Grounded.

A single wire connected the coils of the instruments at opposite ends of the line, the other terminal of each coil being connected to earth.

With such an arrangement of instruments and circuit, it was necessary to speak very loudly at the transmitting end, the sounds received, although clear and faithful reproductions of the transmitted sounds, were very faint and the distance over which conversation could be satisfactorily carried on was short. These conditions stimulated the development of more powerful transmitters, until a host of them had been produced, more or less successful. No attempt will be made here even to catalogue these instruments; but we may classify them according to the principles upon which they operate, investigate the mode of action in each class, and examine in some detail the few which have been in long and general public use.

Every practical transmitter yet invented depends, for its operation, upon one of the following three actions:

1. Magnetic induction;
2. Condenser action;
3. Microphonic action.

1. *Magnetic induction* is at the foundation of Bell's invention. The action is not altogether simple and is still somewhat in dispute. The operation of a magneto telephone has been variously attributed to one or more of these causes:

a. Molecular vibration of the iron core, as in the Reis receiver. This undoubtedly exists, but is so weak that probably in most cases it would be impossible to detect it.

b. Variation in the attraction of the core for the mass of the diaphragm.

c. Action of the spirals of the coil. It would be difficult to separate this last action from the general change in magnetic flow, and indeed no good reason appears why this separation should be attempted. The second cause named is by far the strongest, and in most cases probably the only observable action. As magneto instruments now find their chief use as receivers, further consideration of this action and analysis of their design will be deferred.*

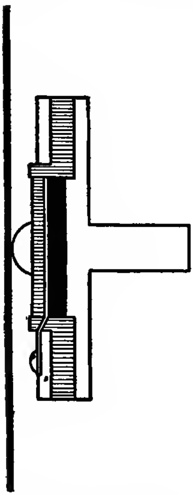
2. Rather early in the history of the telephone it was proposed by Dolbear to use a condenser both for transmitter and for receiver. In such an instrument, the diaphragm would constitute one plate and by its vibrations would vary the distance between the plates. The capacity of the condenser would thus be varied, and pulsations might be made to pass over the line in accordance with the air vibrations. A condenser at the receiving end would respond to the varying charge by a slight motion of the plates, and the pulsations on the line would thus be reconverted into air vibrations.

This arrangement has never met with any degree of success, as the action of the condenser, even under favorable conditions, is altogether too weak for practical use, and the instrument requires very careful adjustment. As a receiver, it can be made to respond very clearly, although the sound is faint, and a powerful transmitter is required.

3. The most powerful transmitters, and, indeed, the only ones which can be said to have given practically satisfactory service, are based upon micro-

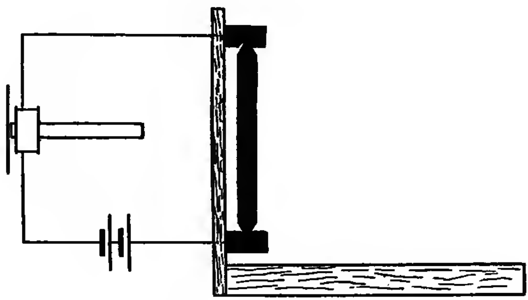
* See page 55.

phonic action; that is, the change in resistance at a point of contact, in correspondence with the air vibrations, and the consequent variation in the current passing through that contact from a constant primary source. It was known, ten years or more before the granting of Bell's patent, that the resistance at an imperfect contact is diminished by an increase of pressure between the two surfaces; but no useful application of this principle seems to have been made until the invention of Edison's "Carbon Transmitter," and the Hughes "Microphone." It had been proposed by Gray to vary the resistance of the circuit in the desired way by the variation in immersed surface of a platinum or carbon rod attached to the diaphragm, and dipping into water or mercury. Experiment showed the effect in such an instrument to be extremely slight, and it is not improbable that even this small effect was due to the microphonic action between the carbon, or platinum, and the mercury.



Working Parts of Edison Carbon Transmitter.

Edison's Carbon Transmitter, patented in 1877, consisted essentially of a rather thin, flat-sided button of specially prepared soft carbon, with contact electrodes on either side, and a diaphragm to receive the air vibrations. The soft carbon button was thus under varying pressure, and it was supposed that the correspondingly varying compression of its substance would produce properly changing resistance. That is, the change of resistance was supposed to take place at the points of contact of the carbon particles in the interior of the button, and not at the surfaces. This very probably was not wholly the case, and the effect it did produce may have been due, in part, at least, to changes at the contacts of the faces of the button with the electrodes.



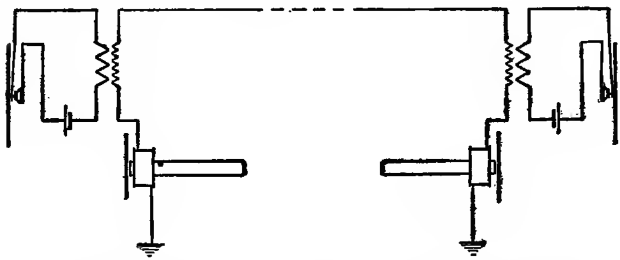
Hughes Carbon Microphone.

The real application of the principle of changing contact resistance was shown clearly in the simple instrument brought out by Professor Hughes in the following year, and called by him the "Microphone." Its most successful simple form is shown in the illustration. By the use of this arrangement, the slightest disturbance of the board which forms the base is transformed into loud noises in the telephone, and the footsteps of a fly, as he walks along the base, can be distinctly heard. This instrument is a "microphone," or device for hearing small sounds, only in the sense that the energy of the current change is transformed into sounds in the telephone, corresponding more or less closely to the primary sounds made upon the board. These primary sounds themselves are not audible in the telephone. The importance of this instrument, at the time, lay in the fact that it brought forward clearly the necessity for a somewhat loose contact, and for the variation of resistance at that contact, and not in the body of the carbon; and the material used, hard carbon, has been found, without exception, the most suitable for such a purpose.

Evidently the magnitude of the effect in any telephone receiver depends upon the range of variation in the current. In a microphone circuit, the only cause for current change is the change in resistance at the contact. To produce the greatest sound effect, therefore, the actual change at this contact must be as great as possible, and it must be as large a proportion of the total resistance of the circuit as it can be made. With a contact resistance changing from ten to twenty ohms, and a circuit whose additional resistance is one ohm, the change in total resistance is from eleven ohms to twenty one ohms.

With constant electromotive force, the current strength would very nearly double under such conditions. If, however, the outside circuit had a resistance of one hundred ohms, the change in total resistance would be from one hundred and ten ohms to one hundred and twenty ohms, or less than one tenth the total, instead of the one half obtained in the first case.

With simple direct circuits under actual working conditions, it is impossible to make the change in



Complete Circuit, grounded, using Microphone Transmitters.

contact resistance as large a proportion of the total resistance of the circuit as it must be to produce useful results. The resistance of the line wire itself is considerable enough to diminish the effect appreciably, and, moreover, there must be inserted in the line some form of receiver, necessarily of still greater resistance. Even under such conditions, the actual current change may be increased by increasing the electromotive force, and this is done in some systems now in use; but a practical limit is set by circumstances to the amount of electromotive force which can be used, so that the best results can seldom be obtained in this way. For this reason, the plan was early adopted of making the microphone circuit very short and its resistance low outside the contact. The primary of an induction coil was inserted in this circuit, and the secondary of the coil, in which high potential alternating currents are induced, was connected to the line. This method, with no substantial modifications, remains in general use up to the present time.*

In a microphone contact there are several actions which take place simultaneously. There is the undoubted diminution of resistance by an increase of pressure, although just what is the immediate physical effect of this increase of pressure is a disputed point. It may be the more intimate connection between two or more particles already in contact, or it may be the making of contact at additional points, as has been claimed by Professor Hughes. Both these effects may occur, although it seems probable that the former is the more important. There is, in addition, the effect of the heating at the contact in diminishing the resistance, if the material is carbon. That such heating does occur, is shown by the occasional welding of metallic contact points; and the

* The "common battery" system, in which a higher battery power is used, without induction coil, was devised for relatively short lines to reduce the expense of equipment and maintenance of batteries.

difference between carbon and metals in the relation between temperature and resistance is one reason for the superiority of carbon, as well as its infusibility and freedom from oxidation.

The microphonic effect has also been attributed to the formation of a minute arc between the points and the change in its length with change of pressure. If "arc" is here used in the customary sense, it undoubtedly interferes with clear reproduction of sound more than it helps. Such small arcs are occasionally formed, as probably everyone knows who has experimented with such contacts. The formation of the arc is immediately made evident by the character of the sound.

Whatever the exact action may be in the microphone contact, all successful transmitters are now based upon it. We may, therefore, classify them and proceed to consider them in some detail. There is an almost endless succession of direct modifications of the Hughes microphone (on which no patent was issued), differing from one another, and from the original microphone, only in the number and positions of the carbon pencils used.

Each of these may be fitted into its proper class, but as none of them is equal, in operation, to the instruments taken as types, no further description will be given

CHAPTER IV.

EARLY SUCCESSFUL TYPES OF TRANSMITTER.

CLASSIFYING microphone transmitters according to the arrangement of their working contacts, we find them divided as follows:

Single contact;

Single contacts in series;

Single contacts in multiple;

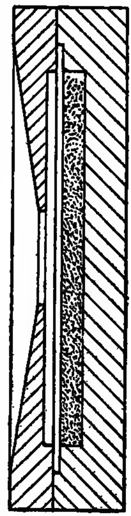
Multiple contacts ("Granular" transmitters);

Single contact in series with multiple contacts.

The Blake transmitter may be taken as a type of the single contact instrument, in which the working portion is very small and approaches the condition which would exist at a single point. There is, therefore, but a single narrow path open to the current, and any attempt to increase the current beyond certain rather small limits results in the production of effects which interfere seriously with the transmission of sound, if they do not prevent it altogether.

This weakness of the single contact transmitter has given rise to many attempts at improvement by multiplication of these single actions, either by putting several single contacts in series or by connecting them in multiple. The failure of the series arrangement seems to be fundamental. It is impossible to arrange a number of contacts in series so that they will all act together. The different contacts will usually be in different phases of vibration at any given instant, and instead of obtaining a multiplication of effect, there will usually be a partial neutralization and a reduction of efficiency as compared with a single contact.

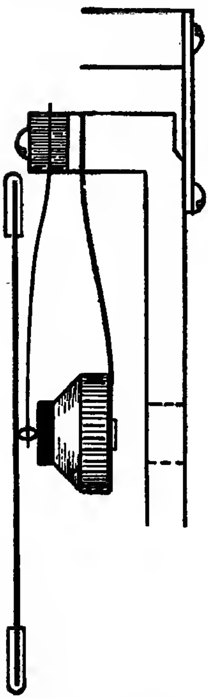
When a number of separate single contacts are used in multiple, the mechanical arrangement is generally intended to be such that all will be in the same phase of motion as the diaphragm at every instant. This can be accomplished to a considerable degree, but not sufficiently so long as each contact is provided with its separate support and connections. As the contacts are brought nearer together, to avoid this difficulty, we approach more and more nearly to the multiple contact or "granular" transmitter.



Working Parts of Hunnings Transmitter.

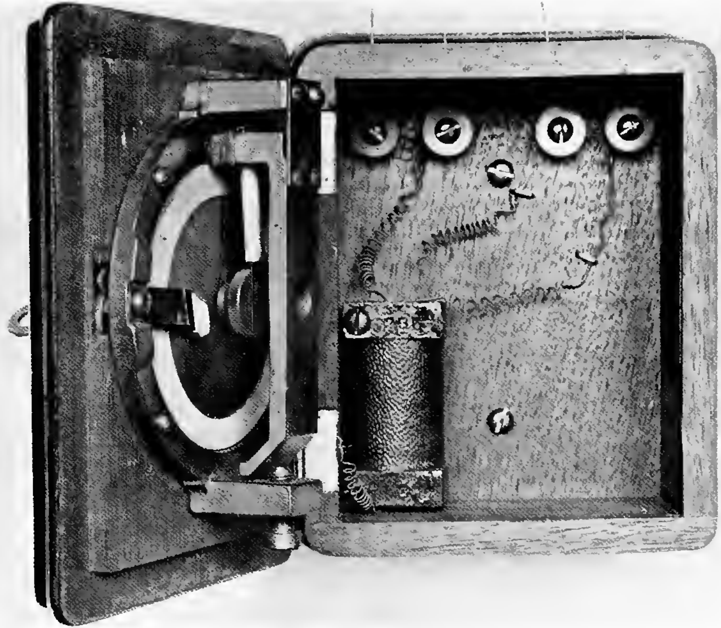
In the multiple contact or granular instrument, of which the Hunnings may be taken as the first successful example, the plan of isolating the separate contacts is abandoned. The working parts consist of granules of carbon making loose and indiscriminate contact with each other and acted upon as a loose mass by the vibrating diaphragm. There are thus many successive microphonic contacts arranged in multiple, all working together and making it possible to use a much stronger current than in any other type of instrument. All the most powerful transmitters in present use are of this type.

The combination of the single contact and the granular instruments was made for the single purpose of converting the Blake transmitter into a more efficient instrument by the change of but one of its parts. The result was an improved instrument when the "granular button"—the new part added—was in good order; but its operation was not commercially satisfactory and it never reached the public. This instrument can hardly be taken as a type, perhaps, unless the button alone is considered as a particular form of granular transmitter. From this point of view it is important.



Working Parts of Blake Transmitter.
Full size.

The Blake transmitter, one of the earliest successful forms, has stood the test of service better than any of its contemporaries and is probably the most familiar of all forms of transmitter to the users of the telephone. The ar-



The Blake Transmitter.

rangement of its parts has remained practically unchanged since it was first put into service and it may be taken as a type of the single contact microphone transmitter.

The working contact in this instrument consists of a button of hard carbon with a flat polished face against which bears the smooth, bright end of an elongated platinum bead. The reasons for the choice of platinum and carbon as materials do not clearly appear, as carbon on carbon gives a somewhat greater working range. The substances used, however, work smoothly and well in practice, if the instrument is properly adjusted.

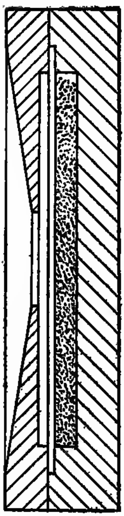
The platinum electrode is supported by a light spring held in an insulated portion of the frame, and the spring of the carbon electrode, in electrical connection with the frame, is stiffer than that which carries the platinum bead. The front side of this bead bears against the diaphragm, the vibrations of which are thus communicated to the contact, and the whole system moves backward and forward, against the pressure of the spring of the back, or carbon, electrode. These springs, which support the electrodes, form part of the primary, or battery circuit, and connection is made with the primary of the induction coil through the hinges of the cover of the box. Provision is made for adjustment by turning a screw which bears against an inclined surface and regulates the pressure of the spring of the carbon electrode.

Nearly all the parts are, however, capable of some adjustment after the instrument is assembled. The rubber-tipped springs which bear against the diaphragm and act as dampers of its natural vibrations may be changed, both as to the places upon which they bear and as to pressure; the position and pressure of each spring carrying an electrode may be altered; and the movement of the adjusting screw finally determines the pressure at the contact. Each of these changes produces a corresponding change in the quality of sound transmitted, and the exact adjustment to produce the desired effect is a matter of experience and judgment. The adjustment of the Blake transmitter is, therefore, easily disarranged by tampering with the working parts, although it is not likely to change in ordinary use, with the box closed. Each instrument is carefully adjusted by experts before it is sent out for use, and those which do not reach the required efficiency are rejected. No attempt should be made by an operator or unskilled telephone user to modify this adjustment, as such attempts are almost certain to result in less perfect action. Transmitters which are intended for use in exchanges are generally more delicately adjusted than those intended for use by the general public.

The Blake transmitter, although it held the field in the United States for many years against all other instruments, has serious faults and limitations. The sounds produced by it are rather weak, so much so that they are often interfered with or completely drowned out by the noises upon any but the best short lines. This may be as much the fault of the line as of the transmitter, but it is highly desirable that a transmitter shall be able to overpower the noises of the ordinary city line, imperfect as it is. The attempt to increase the efficiency of the instrument by the use of higher battery power than two volts is apt to result in the formation of a small intermittent arc at the contact, destroying the speech transmission altogether. The use of a loud voice in speaking, a very natural change when the transmitter is weak in its action, also results in the destruction of transmission, as the contact is thereby broken at every vibration, and the loud rattle thus produced drowns the sounds it is intended to transmit, for which purpose contact must be maintained unbroken. The best results are obtained, with this instrument, by placing the mouth about three or four inches from it and speaking in an ordinary tone. The Blake transmitter cannot be forced.

Another noteworthy transmitter, invented rather early in the history of the art, is the Hunnings. It was the first of the granular type, quite different in principle from the Blake, and although it has never been in general public use in the United States, it is important as the type of instrument from which all the later most successful transmitters have developed.

The construction of the Hunnings transmitter is extremely simple. It consists of two diaphragms of platinum foil, separated by a space of about one tenth of an inch. This space is partly filled with fine granules of hard carbon. The instrument can be held in any position, so long as the carbon makes contact with both diaphragms, and the battery power is limited only by the possibility of the destruction of the carbon by a very strong current. Mechanical protection is afforded the platinum foil by a wire grating placed in front of it, but entirely free from contact.


Working Parts of Hunnings Transmitter.

The most serious fault of the Hunnings lies in the tendency of the carbon granules, irregular in both shape and size, to shake together and become tightly packed so that the contacts are no longer loose. The proper microphonic action is, under such conditions, interfered with, and the sound transmitted is muffled and indistinct. This fault runs through all forms of granular transmitters, to a greater or less extent, and most of the modifications have been made with a view to overcoming it. This is partly accomplished by using granules of nearly uniform size; and they are in some cases shaped artificially into approximate spheres, although the beneficial results of this rounding are not very marked.

The advantages of the granular type of instrument are more clearly seen in modifications of the original Hunnings. In the most recent improvements, the tendency to packing has been almost entirely got rid of; a high battery power may be used and sounds of any degree of loudness will not cause interruption of the circuit. The instruments of this class are therefore very powerful, and the sounds produced are clear and distinct when the carbon is in good condition.

CHAPTER V.

SYSTEMATIC INVESTIGATIONS.

THE facts set forth in the preceding chapter show substantially the situation in regard to transmitters up to the time of the systematic researches, the results of which have been made public. Work in the laboratory of the American Bell Telephone Company, as well as the work of independent inventors, had already developed such transmitters as the Berliner "Universal" and others, leading up to the so-called "Long Distance"; but the investigations were in accordance with the individual experience of the experimenters, as little else was available. The methods were based on little, if any, accurate knowledge of the working of the form of microphone employed or measurements of its efficiency.*

About 1884 a series of experiments was begun at the Massachusetts Institute of Technology, under the direction of Professor Cross, to determine the efficiency of different types of microphone contact; the relation between change in resistance and change of

* For the sake of clearness, the historical order will be somewhat departed from here, and the "Long Distance" transmitter taken up later. See page 45.

pressure; the actual value of the telephone current with different forms of transmitter, and the actual excursion of the electrodes under normal working conditions. These experiments have been continued from year to year since that time, and furnish the most valuable well-ordered information that we possess on the subject of transmitters. Work has been carried on at the same time to investigate the action of receivers. This will be reviewed and discussed later.* Detailed accounts of the methods and apparatus used in all these experiments, and the results obtained may be found in the "Proceedings of the American Academy of Arts and Sciences" from 1885 up to the present time. There will be given here only a summary of the results of each set, with a discussion of the deductions from them.

In the first set of experiments on the value of the telephone current, the Hunnings, Fitch, Blake, Edison and magneto transmitters were tested. The induction coil had a secondary of nearly nine hundred ohms, a much higher winding than that used in practice. The battery power was about three volts in each case, more than is generally used for one or two of the transmitters. The results, therefore, hardly represent actual practice. The different vowel sounds were made by the voice, as nearly uniform as possible in loudness and in pitch, and the current was measured by a sensitive dynamometer. An organ pipe

* See page 55 *et seq.*

blown by a constant blast was also used, but was found to be rather weak. The following table represents fairly the average of the results obtained, the current value being given in the ampère as a unit.

	a	*o*	*u*	*i*
Hunnings	.000737	.000787	.000503	.000213
Fitch	.000450	.000548	.000442	.000264
Blake	.000123	.000144	.000114	....
Edison	.000088	.000123	.000144	.000072
Magneto	.000123(?)	.000260	.000238	.000103

In the experiments of the following year, some modification was made in the instruments, with a view to finding, as nearly as possible, the current value obtained in practice, and the effect of change in pitch. With the "Long Distance" transmitter, an improved instrument of the Hunnings type, using its regular induction coil, the secondary wound to one hundred and forty six ohms, the following values were obtained.

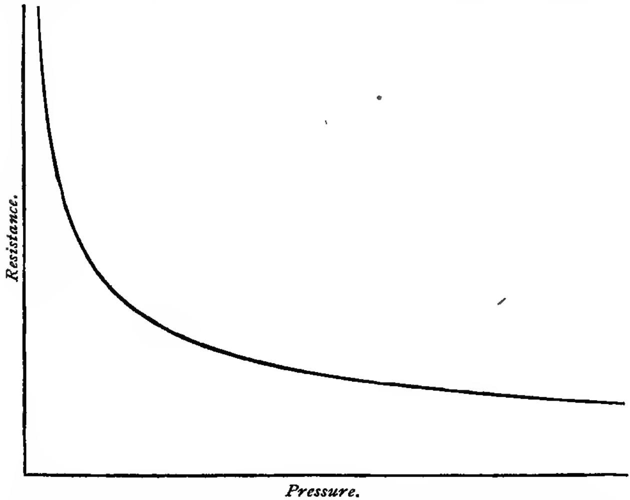
Pitch number.	*a*	*e*	*i*	*o*	*u*
128 *V.*	.00030	.00027	.00025	.00035	.00020
256	.00067	.00062	.00042	.00068	.00054

The effect of raising the pitch of the sound an octave appears, from these results, to be a doubling of the current value.

Such results as those tabulated on page 36 enable us to form an idea of the value of the current sent out by the transmitter, in practice, and to make a rough comparison of different instruments in this respect. As a foundation for our knowledge of the practical working of microphonic contacts, in general, however, and as data upon which to base designs for improvements, they are less valuable than the results obtained by the methods subsequently pursued.

Some measurements had been made, at the beginning of this work upon telephones, to determine the relation between the resistance and the pressure at the contact of a Blake transmitter. The pressure was applied directly, by means of weights, to the contact of a commercial instrument, regularly mounted in its box, and the corresponding resistance measured directly by the usual method. This was a matter of considerable difficulty, owing to the change caused at the contact by accidental vibrations in the building, even the vibrations of street travel being taken up by the contact. The complete series finally obtained gave the curve shown on page 38, the resistance changing from a value of about 25 ohms, with .2 gramme pressure, to about 2.5 ohms with a pressure of 15.0 grammes. The relation between these two varying quantities was found to be expressed by the equation $y^2 x = c$, in which y is resistance, x is pressure, and c is a constant.

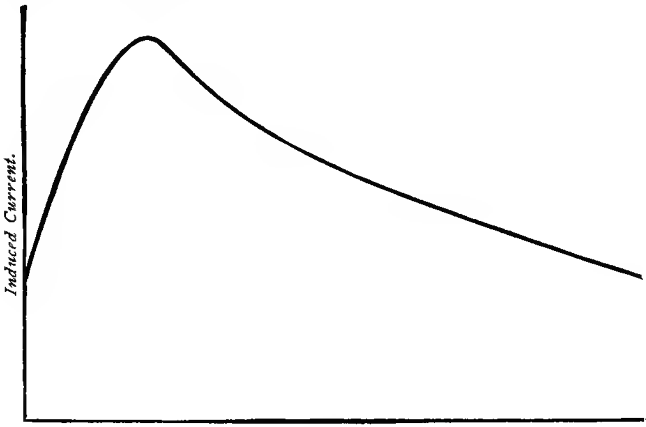
In subsequent work on similar lines the procedure was somewhat modified. Instead of measuring the actual resistance at the contact, as the pressure was changed, the value of the current produced by the transmitter in the secondary of an induction coil was determined by the dynamometer. A special arrangement of contact was devised and an organ pipe was



Curve showing the relation between Pressure and Resistance, in a Blake Contact.

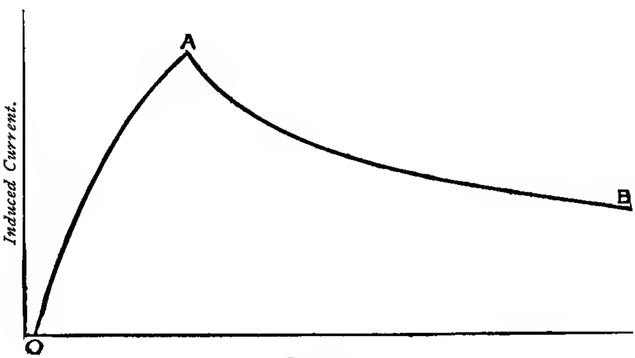
used as a constant source of sound. Under these conditions, results were obtained which are shown by the curve on page 39, the abscissas representing pressure and the ordinates the corresponding currents. Whatever the actual value of the ordinates, they varied in the same manner, and the curve is, in each case, of the same form.

In the interpretation of these results, it was proposed to represent the actual curves, found by experi-



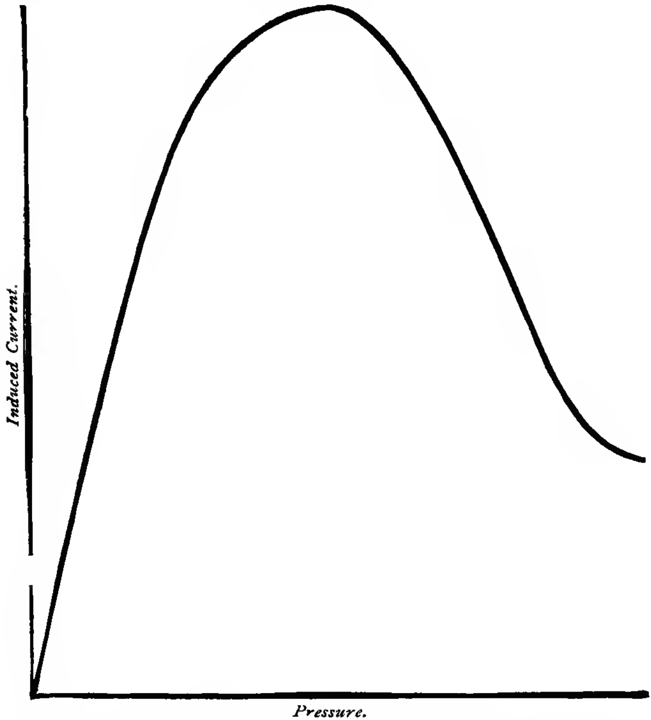
Pressure.

ment, by the typical form *O A B.* In this typical curve it was supposed that the portion *O A* repre-



Pressure.

sented the condition when the contact is incomplete and the transmission consequently imperfect; and *A B* the condition during complete contact,

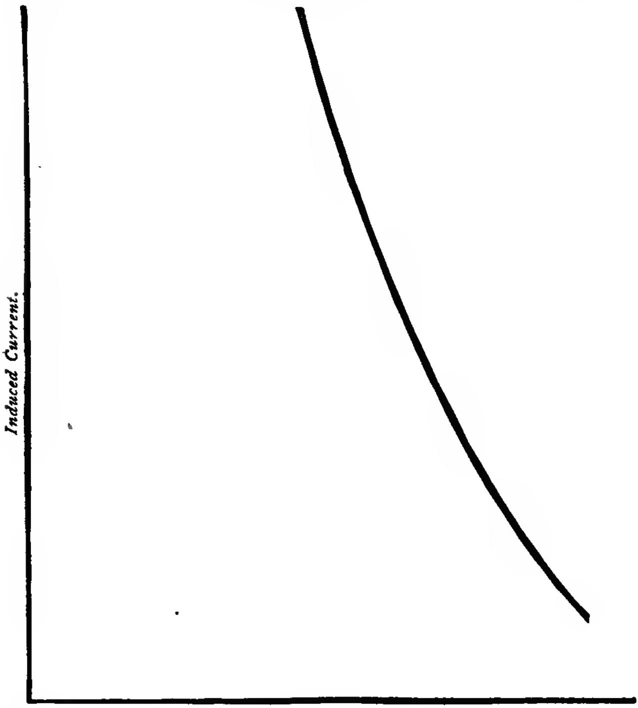


Curve showing the Relation between Pressure and Induced Current, in a Blake contact.

The pressure is changed by the use of weights.

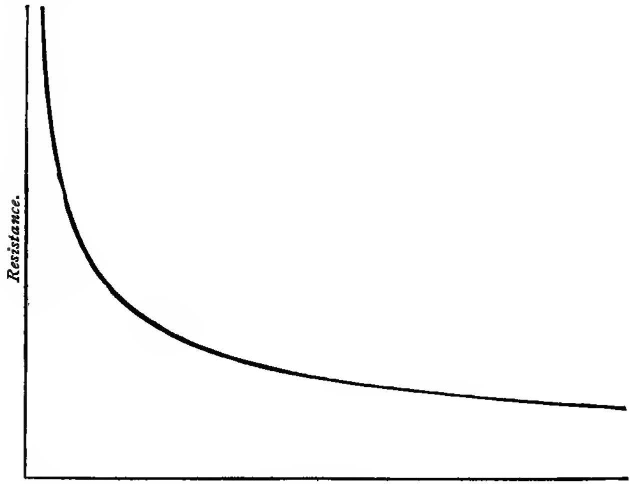
where the transmission is good. The best effects are obtained on *A B*, as near *A* as possible.

This hypothesis, not very satisfactory at best, was overthrown by the investigations of the following year. The form of curve representing the relation between pressure and current was found to be similar



Curve showing the Relation between Pressure and Induced Current, in a Blake contact.
The pressure is changed by the use of a spring.

to that just shown, but it was pointed out that there are not necessarily breaks during the portion *O A*. As the change in pressure is produced by the addition of weights, the mass which has to be moved in the vibration of the contact parts is continually increasing. There are thus two conflicting actions to be taken into account: the effect of the increase of the mass of the back electrode and the effect of the increase of pressure. The form *O A* is determined by



Curve showing the relation between Pressure and Resistance, in a Blake Contact.

the preponderance of the effect of mass-increase while the form *A B* is determined by the preponderance of pressure-increase. The highest part of the curve, parallel with the axis of pressures, shows the point where these two effects are equal.

To add support to this hypothesis, a series of measurements was made with apparatus in which the pressure change was accomplished by the use of a spring, without changing the mass. The results when plotted gave the curve on page 41. This curve shows that the greatest current would be produced with the least pressure.

This conclusion might have been reached from the results of the first set of measurements on pressure and resistance. Although the pressure was produced, in that case also, by the use of weights, the measurement of resistance did not involve the action of mass at all. From the curve then obtained, and reproduced on page 42, the greatest change in resistance, and hence in current, for a given pressure-change, is obtained when the initial pressure is the least.*

* To find the maximum value of current ordinate,

$x =$ pressure Equation of curve, $y^2x = c$

$y =$ resistance

$$\text{Current ordinate} = u = \frac{E}{\sqrt{\frac{c}{x+p}}} - \frac{E}{\sqrt{\frac{c}{x}}}$$

$p =$ constant value of pressure-change due to air vibrations

$$\text{Let } \frac{E}{\sqrt{c}} = a \qquad \text{Then } u = a\sqrt{x+p} - a\sqrt{x}$$

$$\frac{du}{dx} = \frac{a}{2\sqrt{x+p}} - \frac{a}{2\sqrt{x}}$$

This quantity must equal 0 when x is a minimum,
or must equal ∞ when x is a maximum.

In the first case, when the current is a minimum, $p = 0$, which is sufficiently evident from the conditions, without proof.

$$\text{Therefore } \frac{du}{dx} = \infty \quad \therefore \frac{dx}{du} = 0$$

$$\frac{dx}{du} = \frac{\sqrt{x} \cdot \sqrt{x+p}}{\sqrt{x} - \sqrt{x+p}} = 0 \qquad \therefore \sqrt{x} \cdot \sqrt{x+p} = 0$$

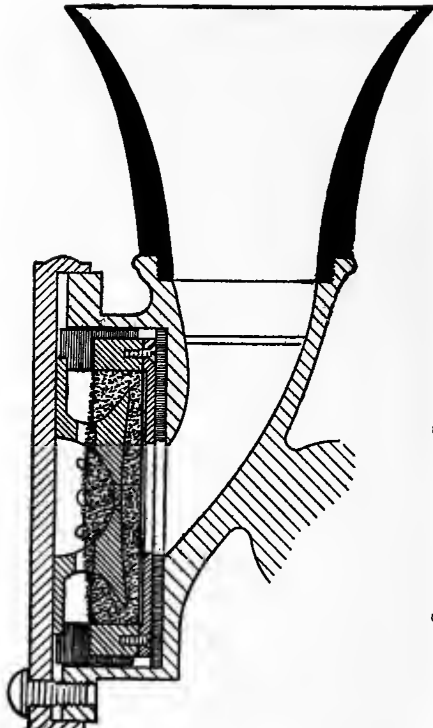
or $x = 0$.

The progress of this investigation illustrates the difficulties of interpreting the results of experiment. The mixing of the effects of mass and of pressure, although the matter seems clear enough now, was a natural error and it retarded the work for nearly a year. When the distinction was pointed out, however, the deduction from it should have been simple and evident. Following out the effect of increase of mass alone, as increase of the mass of the back electrode produces a continually increasing effect upon the current, the increase of mass to a maximum should give the maximum current effect. Such an increase results in making the back electrode rigid and gives at once the "solid back" transmitter. The "long distance" transmitter, already in use, possessed this feature, but the effectiveness of its action in this respect was impaired and its importance concealed by serious faults of another nature. The search for a remedy led into a development along somewhat different lines, and the "solid back" was not brought out until some years later.

CHAPTER VI.

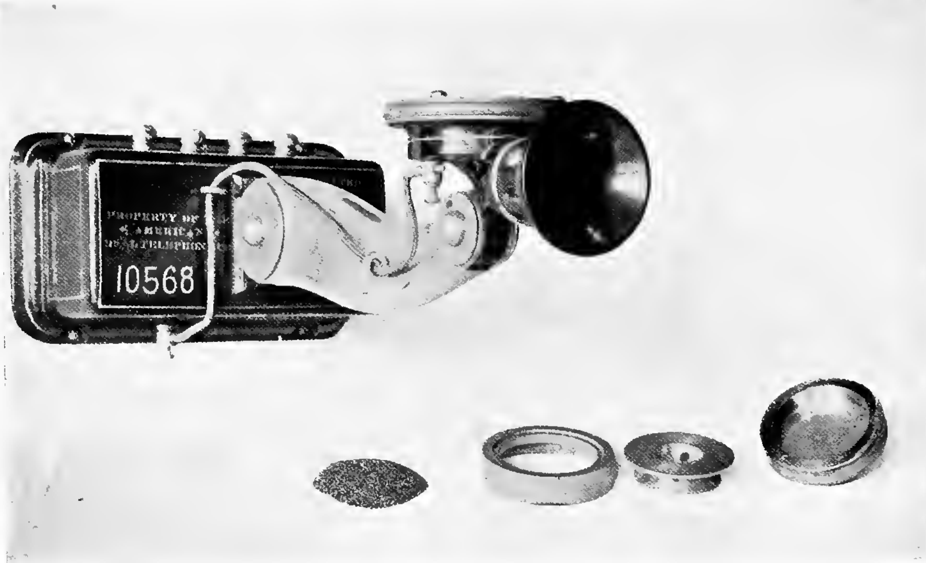
GRANULAR TRANSMITTERS.

ALTHOUGH the single contact transmitter, as exemplified in the Blake, reached its permanent form at an early period, the granular instrument seems to have presented too many complications in action to permit such rapid development. The superiority of transmitters of the Hunnings type, in power and in possibilities in other ways, was early recognized, and continuous efforts were made to effect such improvements as would make a commercially successful instrument. One of the first changes was the substitution of a rigid metallic electrode for one of the platinum diaphragms and the turning of the layer of carbon granules into a horizontal position. Within certain narrow limits as to general form, almost every conceivable modification of shape of this electrode was tried. The general idea underlying all this work was that the vibration of the diaphragm should itself operate to shake up and loosen the carbon granules and thus avoid the difficulty of "packing," or the wedging of the carbon tightly between the electrodes. The massive upper electrode was given the form that it was thought



Section through Long Distance Transmitter.

Full size.



Carbon Granules. *Insulating Ring.* *Electrode.* *Platinum Diaphragm and Metal Clamping Ring.*

THE "LONG DISTANCE" TRANSMITTER.

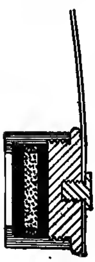
would best facilitate this action; the carbon was most carefully prepared and the granules were assorted to close uniformity in size; and the thickness of the layer was varied until the best effect was obtained. The form and proportions finally reached by experiment are shown in the diagram and plate.

The upper electrode, of brass, gold plated, has a deep cup-shaped cavity extending into its body from the top. This cavity communicates with the working space below by means of a vertical hole in its base and by a series of holes about half-way up the side. Sufficient carbon is used, of a size between 60 and 80 to the inch,* to fill completely the space between the platinum diaphragm and the lower face of the brass electrode, and to extend about half-way up the walls of the cup, not quite covering the circular row of holes. It was thought that the vibrations of the diaphragm would cause the carbon to circulate upward through the central hole, outward and downward through the holes above. Whether such action really takes place in this instrument to an appreciable degree is doubtful. An electromotive force of 4 to 6 volts was adopted, with as low battery resistance as possible, the induction coil having a resistance, in its primary, of about 0.5 ohm, and in its secondary of about 150 ohms.

Transmitters of this design were put into service,

* That is, the grains will pass through a sieve of 60 meshes to the inch, but are retained by a sieve of 80 meshes.

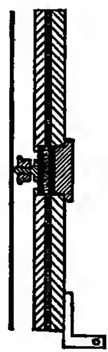
and, when in good condition, gave excellent satisfaction. They were used for some years on the long lines, for which the Blake was much too weak, and occasionally for the better class of service on short lines. Individual instruments, however, were given to obstinate fits of inefficiency, in spite of the most vigorous shaking up. Although the sounds transmitted might be loud enough, they were almost inarticulate, the speech received being thick and often unintelligible; and, in general, the old fault of "packing" had not been overcome. Further experiments were made with new modifications in the shape of the electrode, without result, and a diaphragm of somewhat greater thickness was tried, to make the bulging of the soft platinum foil more difficult. No material improvement resulted from these attempts, and although the seriousness of the defects of the "long distance" transmitter, the best instrument produced up to that time, was a great stimulus to investigation, matters were in this condition when the researches at the Massachusetts Institute of Technology, already described, were made public.



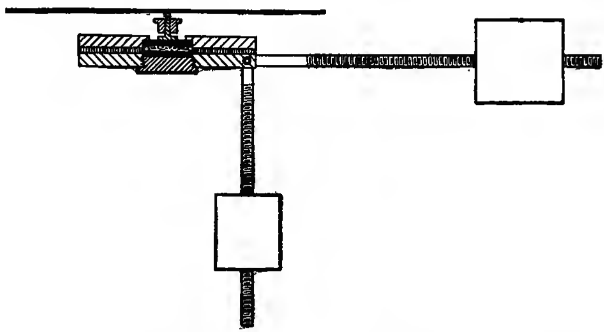
Granular Button.

The carbon contact discs are separated, at their edges, by a felt ring.

Meanwhile, the almost universal demand for a more efficient transmitter had prompted the attempt to convert the Blake into a granular instrument at the smallest possible expense. The result of this attempt was the so-called "granular button." This was a small cylindrical case containing granulated carbon between two hard carbon disc electrodes. It was designed to be screwed upon the back spring of the Blake contact, in place of the regular carbon electrode. Because of the small size of the granular button and the conditions under which it was used, but a moderate battery power was possible. With current enough to produce really loud talking, the button became very hot and was at its best when smoking hot, just before it was consumed. It was extremely subject to the characteristic fault of "packing," and although it was used to some extent by experts and operators, the instrument never came into general use, even in exchanges. It is important, as subsequent developments were somewhat in accordance with its general design, and the working parts of the best transmitters now in use have a greater resemblance to the granular button than to the type represented by the "long distance." It was, however, the perfection of details as well as the adoption of the rigid back electrode, which has made these later instruments successful.



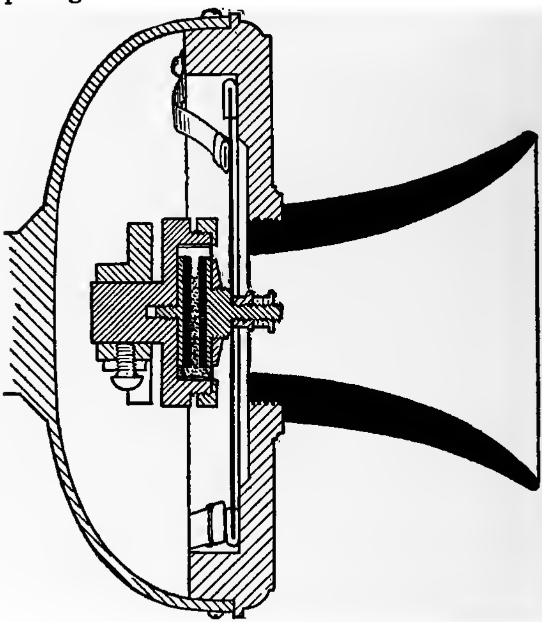
Some attempts were made, in laboratory investigation, to combine the granular button with other devices by which the normal pressure could be regulated and by which the packing of the carbon could be avoided. There was, however, the same confusion as before in the effects of mass and of pressure. A heavy metal plate, through the centre of which the button was screwed, was pivoted at a point back of its centre, and a pin, permanently connected to the front disc of the button, was held against the diaphragm by the weight of the plate. The carbon granules could be shaken up and loosened by throwing back the plate when the instrument was not in use. Although this transmitter did not reach a form practicable for use, it contributed its share in the progress of the development of a new instrument.



Another experimental form, which was intended to show the relative effect of mass and of pressure, consisted of a granular button mounted in one end of a lever. The diaphragm was placed horizontally, as was the lever; and from the pivot another arm projected vertically downward. On each arm was a movable weight, and it was thus possible to change either the mass-resistance (the moment of inertia) or the initial pressure by a proper adjustment of these weights. With this arrangement, it was found that the efficiency increased continuously, with an increase of inertia up to the limit of the apparatus. With a longer vertical arm or a greater mass upon it, which had no effect in changing the initial pressure, but which changed only the mass-resistance of the moving parts, a still further increase would undoubtedly have been obtained.

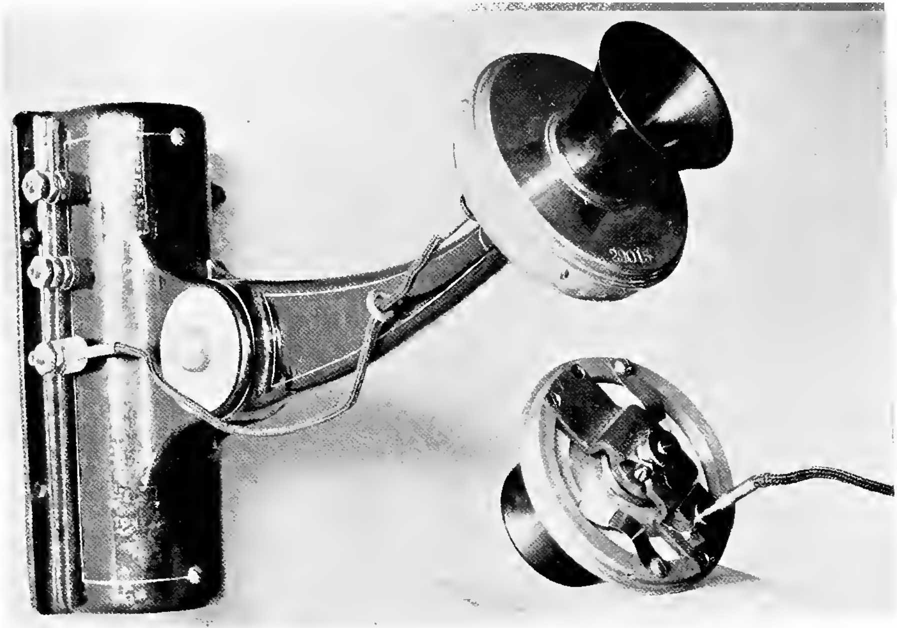
The further development in this direction seemed to be slow. Although the general lines along which the work was to proceed were fairly clear, it was necessary to find the best dimensions, the best relations of parts, suitable material for each part and a good mechanical arrangement. These details were very thoroughly and carefully worked out by the late Anthony C. White, in the laboratory of the American Bell Telephone Company, and the transmitter which was produced as the result of his labors was named the "Solid Back." It is by far the best instrument, in every respect, that has yet been put into service.

The construction of this instrument is simple. The back electrode consists of a mass of brass, firmly held in a substantial brass bridge and having recessed in it a chamber for the working microphone. Rigidly connected to the bottom of this chamber is a hard carbon disc constituting the back contact. A similar carbon disc constitutes the front contact, and is fast to the diaphragm. To secure this arrangement with proper insulation and provision for preventing the escape of the carbon granules, a mica disc is clamped against the outer surface of the front carbon



Section through "Solid Back" Transmitter.
Full size.

disc by a brass collar, and its edge is held by similar means against the front edge of the back electrode, closing the chamber. The use of this mica disc solved several difficulties at once. It made it possible to leave a space between the piston-like front electrode



The "Solid Back" Transmitter.

and the walls of the chamber, which was found to be necessary in order to avoid packing of the carbon granules. It is sufficiently elastic without offering any undue resistance to the motion of the front contact, and it is not affected by the heat in the microphone when in operation. One of the most serious difficulties in the granular button was the rapid deterioration, because of the heat developed, of the felt ring which was used to separate the contact discs. As the elasticity of this ring was depended upon to react against the inward vibrations of the diaphragm, the loss of this elasticity or the complete destruction of the ring, which sometimes occurred, necessarily put an end to the proper action of the button as a transmitter. In the "solid back" transmitter there is no material used which is affected at all seriously by heat and no deterioration from that cause is to be feared. The carbon granules do not completely fill the containing chamber, and the annular space left between each disc and the walls seems to be of importance in preventing packing. Rubber-tipped damping springs prevent the vibration of the diaphragm in its natural period.

The circuits for this transmitter are substantially the same as for the "long distance." The induction coil is slightly modified and a slightly higher battery power can be used successfully. Many other forms of granular transmitter have appeared from time to time, but the principles already developed apply equally to them, and none of them has the certainty of action and the power of the "solid back."

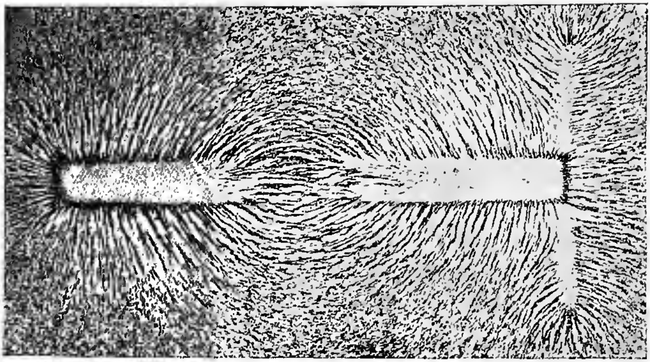
In designing a telephone, it is necessary to consider the acoustic properties of the parts as well as their electrical properties. The form of the sound waves striking the transmitter diaphragm is more or less modified in transmission by the parts of the transmitter. In addition to the effect, in producing such changes, of the microphone itself—the quality of sound from a single contact instrument is quite different from that from a granular transmitter—the size and shape of the mouth-piece and any other cavities which are capable of action as resonators have a more or less important effect, unduly strengthening the components of the wave whose periods of vibration coincide with their own. This causes a change in the relations of the components of the wave as it leaves the transmitter and a consequent change of quality in the sound received. The diaphragm will have a similar effect if it is too rigid to take up readily the vibrations of higher frequency or if its own natural vibrations are not prevented by the damping springs. Such actions as these are probably more important in the receiver than in the transmitter; but the mouth-piece must be so designed that it will reinforce as evenly as possible all the vibrations which come to it, and the diaphragm must be of such thickness and the damping springs so placed as to avoid selective action.

CHAPTER VII.

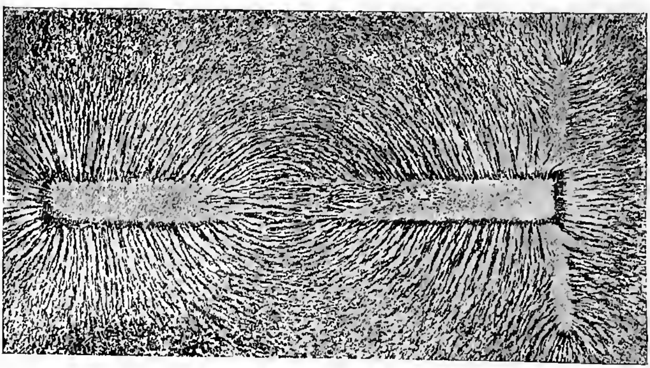
MAGNETO INSTRUMENTS.

THE causes of the action of the magneto telephone, whether used as transmitter or as receiver, have already been mentioned. The essential parts of the instrument are a soft iron diaphragm, placed near the end of a magnet, upon which is a coil of wire. The diaphragm is thus in a magnetic field, and when the instrument is used as a transmitter, the motion of the diaphragm causes a redistribution of the flow of magnetic force. This change in the flow of force, although slight in magnitude, is very rapid, corresponding to the rapidity of the sound vibrations; and the electromotive forces induced by the magnetic changes will also correspond exactly with the sound vibrations, although slightly behind them. The periodic curve, representing the variation in electromotive force, is then of exactly the same form as that representing the sound waves—of which some examples are shown in the first chapter—and if the wire coil forms part of a circuit, an alternating or undulating current is caused to traverse the circuit, its variations corresponding exactly with the motion of the diaphragm, due to the sound waves. The magnitude of the induced electromotive force, and, therefore, that of the induced current, depends upon the rate of change of the flow of magnetic force through the coil.

A definite idea of the character of the change in the distribution of magnetic force, although the magnitude of the change is here much exaggerated, may be obtained from the accompanying illustrations. These are from photographs of "magnetic phantoms," so-called, obtained with a bar magnet and a section of soft sheet iron, to represent the relations of the magnetic parts in the hand telephone. In the first case, with the diaphragm very near the pole of the magnet, the direction of the magnetic force, at the point which is, in the telephone, surrounded by the coil, is slightly inclined toward the other pole of the magnet. As the diaphragm is moved farther and farther from the pole, the direction of the magnetic force becomes less inclined toward the opposite pole, until, with the air gap in the last of the four figures, the force through a great part of the coil is even slightly inclined away from the opposite pole, and toward the diaphragm. The lines of force may be said, in a sense, to follow the motion of the diaphragm, and to wave back and forth across the turns of wire. At the same time, the force flowing out of the diaphragm changes its direction in a similar way, and some of these lines, also, will cut the turns of wire in their motion. Although, as has been pointed out, the change in the magneto telephone is very



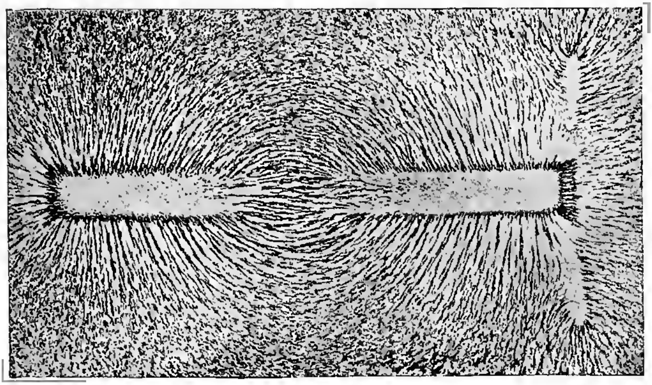
I.



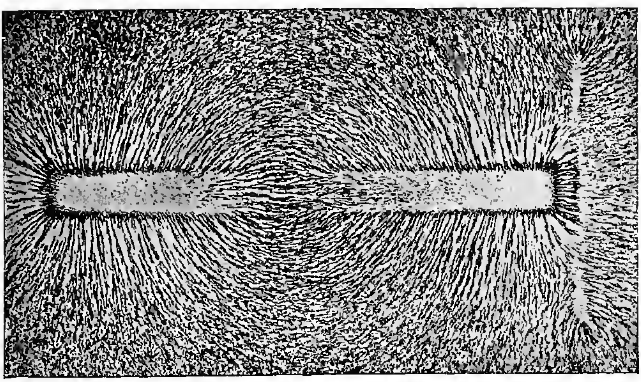
II.

MAGNETIC PHANTOMS.

Showing change in direction of lines of force, with motion of diaphragm.



III.



IV.

Magnetic Phantoms.

Showing change in direction of lines of force, with motion of diaphragm.

much less than that shown in these figures, it must be of the same character, the change in the direction of the lines closely following the motion of the diaphragm. It should be noted, however, that these illustrations show the change in *direction* only, and not the change in the magnitude of the force.

When the magneto telephone is used as a receiver, the opposite action takes place. The strength of field changes in accordance with the variation in the current through the coil, producing a varying pull upon the diaphragm and thus converting the current waves, by means of the vibrations of the diaphragm, into air vibrations.

In order, therefore, to make the instrument as powerful as possible, the diaphragm must be so placed in the field, and the strength of the magnet must be such, that a given motion of the diaphragm will produce a maximum change in the distribution of the magnetic force, when used as a transmitter; or so that, when used as a receiver, the variation in the current in the coil shall cause a maximum relative change in pull upon the diaphragm. A rough mathematical investigation shows that the greater the value of the initial magnetization, the greater will be the change in pull upon the diaphragm.*

* The force acting upon the diaphragm is proportional to the square of the magnetization. If the initial magnetic force is $\mathbf{H}$, the initial pull is $\mathbf{H}^2$. With increment of magnetization, $\mathbf{h}$, the pull is $(\mathbf{H}+\mathbf{h})^2$, ∴ the difference, or change in pull $= (\mathbf{H}+\mathbf{h})^2 - \mathbf{H}^2 = 2\,\mathbf{h}\,\mathbf{H}+\mathbf{h}^2$; and this quantity increases without limit as $\mathbf{H}$ increases.

There are practical limits set to the value of **H** by other considerations, which seem to have been overlooked by the designers of most of the modifications of the original magneto telephone. In most of these modifications, the attempt has been made to increase the power of the instrument by an increase in the strength of field, or the flow of force through the diaphragm, without regard to the condition of the diaphragm itself with respect to saturation; whereas the approach of the diaphragm to a condition of saturation is most important in its effect upon the rate of change in the flow of magnetic force through the coil. One of the first changes to be tried, and one which has probably been tried many times, is the modification of the magnetic circuit so as to polarize the diaphragm. A discussion of the sources of variation in a magneto telephone will show why such an arrangement can never give the effect desired or, of itself, produce a successful instrument.

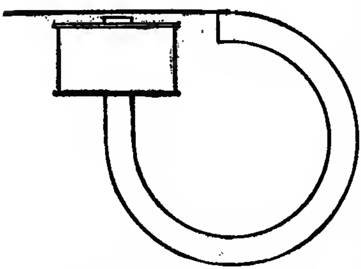
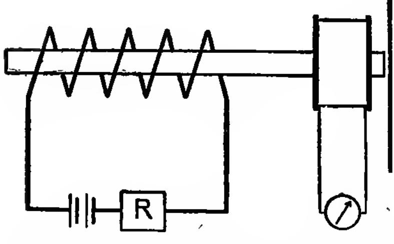


Diagram of Polarized Receiver.

As the strength of the field magnet of the instrument is increased, the first direct effect, regarding this part alone, is to increase the number of lines of force cut by the diaphragm and hence to increase the strength of the induced current. Continuing this increase in magnetization and assuming that the diaphragm is always far from saturation, the point is finally approached at which the magnet is saturated. The amount of variation in strength of field due to changes in the current strength in the coil, or the change in the flow of force through the coil due to the movement of the diaphragm, would be diminished as this point is approached. Practically, however, the saturation point of the magnet can never be closely approached, because the diaphragm becomes saturated so much sooner. It is the approach to saturation of the diaphragm which sets a limit to the strength of the magnet, for there will be the same decrease in effect, as the saturation point of the diaphragm is approached, that would be found in the case of saturation of the magnet, and for a similar reason. Not only, therefore, is there no gain by polarizing the diaphragm to increase the normal flow of force through it, but there may be an actual decrease of power.

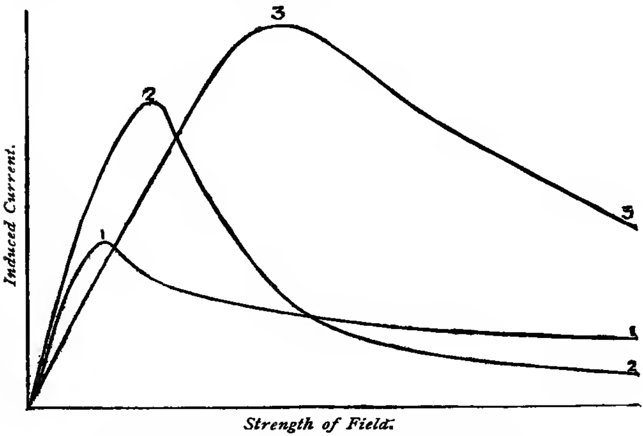
The question at once arises, therefore, what should be the relative magnetization of the diaphragm—what proportion of saturation—to produce the greatest effect? What should be its size, thickness, and distance from the pole piece, and, in the complete practical instrument, what is the exact relation between strength of magnetic field and effectiveness? The answer to this last question really involves the determination of the other points named; and although it is not to be expected that the various inter-relations can be so exactly formulated, in any investigation of this character, as to avoid the necessity for considering adaptability to a given purpose, careful analysis will enable us to separate the effects of modifications in the different parts and so to proportion these actions as to lead to the desired result.

Research along these lines has been carried on at the Massachusetts Institute of Technology, parallel with the investigation already described, in regard to microphone transmitters.* As stated by the investigators, "Our investigations include a study of the changes in the strength of the current produced by a magneto transmitter under varying conditions of magnetization, and of the magnitude of the momentary changes in the magnetic condition of the core of the receiving telephone when subjected to the action of undulatory or other brief currents, as influenced by the strength of the primitive permanent magnetization of the core." A soft-iron core about 4½ inches long was



*Proceedings of the American Academy of Arts and Sciences, November 14, 1888; November 12, 1890; May 24, 1892; January 11, 1893.

used, with suitable arrangements for changing its magnetization and for measuring the strength of field produced by it. A definite throw of the diaphragm, accomplished by means of a cam and falling weight, caused a momentary current in the fine wire coil, of about 100 ohms resistance, placed as usual in practice



Curve No. 1, one diaphragm of ferrotype iron, No. 31.
Curve No. 2, two diaphragms of ferrotype iron, superposed.
Curve No. 3, three diaphragms of ferrotype iron, superposed.

about one end of the core. The diaphragm occupied its usual position and was $2\frac{5}{16}$ inches in diameter. Measurements were made of the magnetization and of the momentary current produced in the fine wire coil, giving a series of correlated values of these two quantities for each of the cores and each of the diaphragms used. Cores of Norway iron, Bessemer steel and untempered mild steel were used, and the thickness of the diaphragm was varied through a considerable range. Some of the results are shown in the accompanying curves.

Examination of these results shows that the first effect of increased magnetization is a rise in strength of the induced current at a rather rapid rate, at first constant and then diminishing up to the maximum value of the current. From this point the current decreases, rapidly at first, more slowly afterward. We see, moreover, that the degree of magnetization at which the current reaches its maximum value varies with the mass of the diaphragm, although the general form of the current curves is the same in all cases; and that the greater the mass of the diaphragm, the higher is the maximum value of the current. It is to be remembered, however, that this results from a motion of the diaphragm of constant amplitude and not from the vibration due to the action of sound waves of constant intensity. In this respect, therefore, these results cannot be applied directly to practice.

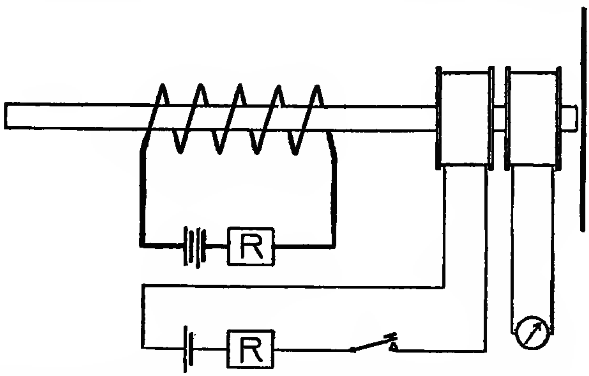
The occurrence of a maximum current at a point where the magnet core was found to be less than half saturated can be due only to the approach of the diaphragm to saturation. As this condition is approached, the change in the flow of force through the diaphragm, as it moves to and from the magnet, becomes less and less, opposing the increase due to the increasing strength of field. It appears, then, that in the usual form of magneto instrument, the degree of magnetization of the core is relatively unimportant, and that it is the relative saturation of the diaphragm which determines the point at which the maximum current occurs. This is still more clearly shown by the results obtained by the use of thicker diaphragms. These results show at once "that the greater the strength of the field required to saturate the diaphragm the greater is the strength of the field at which the maximum current occurs," and consequently, the higher is the value of this maximum.* Subsequent experiments, in which some slight defects of apparatus were corrected, and in which the same ground was covered, gave results corroborative of those just described.

In investigating the action of the magneto telephone as a receiver, the apparatus employed was similar to that already described, two fine wire coils instead of one being placed near one end of the core. One of these coils corresponded to the coil of the ordinary receiver, and through it could be sent a current of the same order of magnitude as the telephone line current. The other fine wire coil served for measurement. From the current induced in it, the effect of the line current in changing the magnetization of the

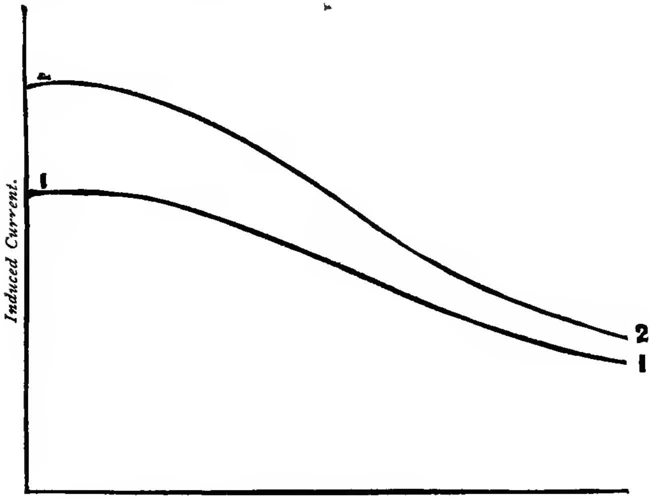
* The peculiarity of the curve obtained with two diaphragms as compared with those of one and three is ascribed to the lack of both magnetic and mechanical continuity. The greater thickness was secured by superposing two and three diaphragms respectively, each of the thickness of that used alone, 0.01 inch.

core could be determined. The strength of field was varied as in the previous experiments. The investigation of the actual motion of the diaphragm, as influenced by these conditions, was undertaken still later.

Observations made upon the core alone, without a diaphragm, showed its behavior under varying degrees of magnetization, and gave the relation between



strength of field and the change produced in it by a momentary current of constant value. This relation is shown by the lower curve in the figure. Corresponding sets of measurements were then made with diaphragms of different thickness. One such set of results will show the character of the effect produced by the addition of the diaphragm. The upper curve in the figure is plotted from the observations made with a diaphragm of ferrotype iron such as is generally used. With the core alone, the induced current remains practically constant for a time and then diminishes at an increasing rate, which finally becomes nearly constant. This would be expected, as the core was far from saturation and the line current,



Strength of Field.

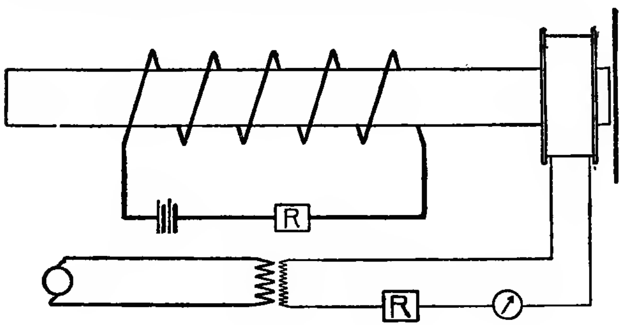
Curve No. 1, for receiver without diaphragm.
Curve No. 2, for receiver with one diaphragm of ferrotype iron.

Magneto Receiver.

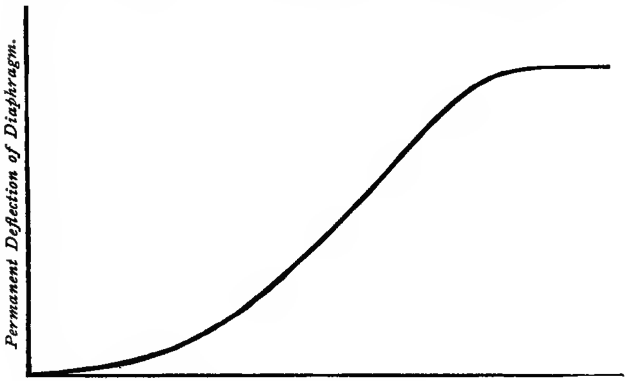
Relation between strength of field and the change produced in it by a momentary current of constant value.

of uniform value, became a smaller and smaller proportion of the total magnetizing current, as the magnetization was increased. The addition of the diaphragm caused the induced current to rise slightly at first, and then to diminish at a greater rate than when the core was used alone. This action is due to the same causes that have been explained in connection with previous experiments. It was found that, in general, the value of the maximum current was greater and the subsequent fall more rapid, with the thinner diaphragms, probably because of their greater motion for a given line current.

These results are of value, as they enable us to analyze, in part, the action of a magneto telephone receiver; but they do not show the acoustic effect of the receiver and therefore are less directly interesting than those which follow. These give us a direct relation between the magnetization of the core and the amplitude of the motion of the diaphragm.



In these experiments the instrument used was of the same general form as in the previous work. The core carried a magnetizing coil and a fine wire coil of about 100 ohms resistance. The line current was obtained by induction, the primary current being furnished by an alternating-current dynamo. The line current was therefore somewhat greater than that produced by even a powerful transmitter; but the character of the results was substantially the same that would have been found with the current of usual strength. The motion of the diaphragm was

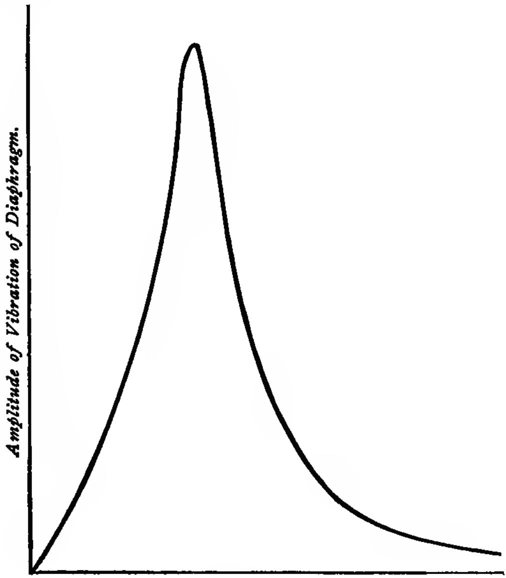


Curve showing the Relation between Strength of Field and Permanent Deflection of the Diaphragm.

observed and measured by means of a microscope, using the stroboscopic method.*

* This method is very generally used for the exact measurement of motions which are too rapid to be followed directly by the eye. An arrangement is used by which the moving body is periodically illuminated, the period of the illumination being nearly but not quite the same as that of the vibrating body. If the periods were exactly the same, the body would be seen in exactly the same phase at each vibration and would appear to be at rest. If the periods differ but slightly, the vibrating body appears to move slowly through its whole course, the rate of the apparent motion depending upon the difference in the two periods. By this method a very rapid motion can be exactly measured with ease.

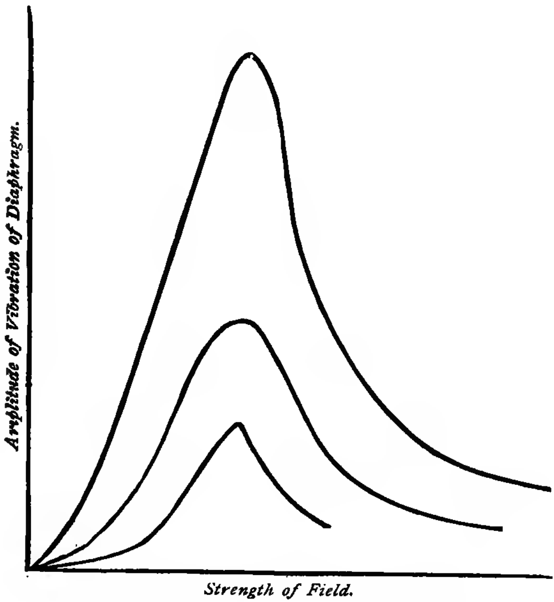
When the core is magnetized, the first effect observed is a permanent deflection of the diaphragm, which is pulled toward the magnet by an amount depending upon the strength of the field, the rigidity of the diaphragm, and its initial distance from the pole. The relation between this fixed deflection and the strength of field is shown by the curve.



The relation between the value of the magnetizing current and the amplitude of vibration of the diaphragm was investigated, and it was found that the excursion of the diaphragm first increased to a maximum, and then decreased. The general relation between strength of field and excursion of the diaphragm is shown by the curve, which is similar in form to those obtained from previous work. The point of maximum excursion was reached when the magnet was far below saturation.

The actual value of the excursion of the diaphragm, under the usual conditions of operation, was not measured, as the line current was in every case considerably stronger than the strongest telephone current. From the results obtained, however, it was computed that, with a strong telephone current, the excursion of the receiver diaphragm is probably somewhat less than two one-thousandths of a millimetre (0.002 mm.).

Still later investigations of the relation between strength of field and motion of the receiver diaphragm confirm the results just described. In order that actual conditions might be reproduced as nearly as possible, a powerful microphone transmitter furnished the line current. The actuating sound was produced by an organ pipe, uniformly blown, and the circuit was as usual in practice, with the standard induction coil. The results obtained agree, in their general character, with those already given. With a line current of uniform value, the amplitude of motion of the diaphragm rises to a maximum, and then falls, rapidly at first, then more and more slowly, until a very small but nearly constant value is reached. Each value of the line current gives, as would be expected, a different curve; but the maxima, although not of the same value, occur at the same point of magnetization. This point, at which the maximum motion occurs, is not the same as in the previous case, as the diaphragm was placed nearer

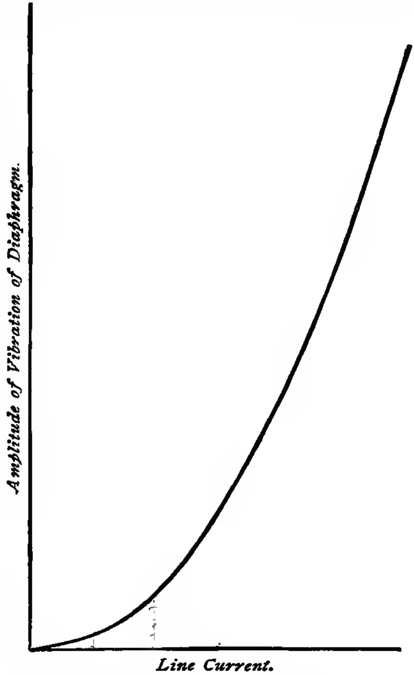


Line Current Produced by Transmitter.

Maximum efficiency occurs at the same point of magnetization for all values of the line current.

the pole piece. It therefore reached saturation more quickly and the influence of this condition was shown by the occurrence of the maximum motion at an earlier stage of magnetization. Evidently, the strength of the magnet, to produce the greatest acoustic effect, cannot be fixed without considering the thickness and diameter of the diaphragm, and its distance from the pole.

An interesting set of observations was made, with an ordinary magneto receiver, to determine the relation between the value of the line current and the excursion of the diaphragm. The results are plotted in the accompanying curve, which is very closely parabolic, and shows the motion of the diaphragm to be proportional approximately to the square of the current, with the values used.*

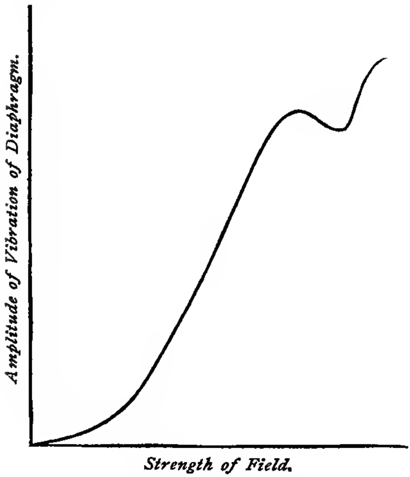


Regular Hand Telephone.

Curve showing the relation between the value of the line current and the amplitude of motion of the diaphragm.

* See curve, page 67, showing the relation between magnetizing current and permanent deflection of the diaphragm. The total magnetic

With the diaphragm placed nearer the pole piece, the deflection produced by a constant value of line current, as the strength of the core was increased, rose to a maximum as before, began to fall and then increased again to a second maximum, higher than the first. This action was ascribed by the investigators to the assumption by the diaphragm of a "new position of equilibrium under the increased pull of the magnet. The effect of increased proximity of the diaphragm to the core more than makes up for the opposing effect of a closer approach of the diaphragm toward satura-



induction due to any current, depends not only upon that current, but upon the previous magnetic history of the magnetic substance. Within the limits of magnetization of the receiver magnet, the total induction will be very nearly proportional to the magnetizing current, and the force acting upon the diaphragm will be very nearly proportional to the square of the total magnetization. With the core far from saturation, therefore, we should expect this force, and the motion of the diaphragm in response to it, to increase at a somewhat greater rate than the square of the line current; that is, within the limits of elasticity of the diaphragm.

tion." It is not quite clear why there should be such a sudden change in the permanent deflection of the diaphragm, as no such action is seen in the curve showing the relation between strength of field and permanent deflection. Possibly the elastic limit of some part of the diaphragm is passed and a "buckling" follows.

CHAPTER VIII.

DESIGN OF RECEIVERS.

In the design of a magneto receiver for any given purpose, it must be borne in mind that the effect of a change in the proportions and relations of the parts is twofold. There is the magnetic effect, which has been investigated as already described, and which can be measured without undue difficulty, and there is the acoustic effect, which, in any investigation involving measurement alone, must be ignored to a great extent. Although it is, perhaps, possible to measure the acoustic effects of changes in parts, it is scarcely feasible to do so, and they must remain matters of judgment and estimation.

It is, of course, desirable that a receiver should reproduce, in sound, the waves that come to it from the transmitter, without distortion or any selective action. As these waves are made up of vibrations running through a considerable range of frequency, there are several harmful actions possible which demand careful consideration quite apart from the matter of magnetic efficiency. These possibilities are principally the damping by one or more of the parts of the receiver of some of the component waves and the augmenting of others by resonating action.

A thick diaphragm is rigid, and, therefore, although it may be made to have a considerable motion and produce a loud sound, the higher overtones are quickly extinguished and the result is a muffling of the sound, a lack of sharpness and clearness, and a corresponding change in the quality. In any case, the natural tone of the diaphragm must be so far suppressed as not to preponderate over the other tones present in the sound. The cavities in the instrument, also, must be so shaped as to strengthen as equally as possible all the component tones.

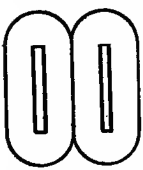
So far as clearness and sharp articulation are concerned, a thin diaphragm shows always a marked superiority over a thick one. This sharpness may be slightly increased still further by inserting a metal ring in the cap and another in the case, so that the diaphragm is clamped between two hard edges. Even here, however, if the diaphragm is made too thin, although it responds beautifully to the waves of higher frequency and gives sharp and clear articulation, the quality of transmitted sound may not be faithfully reproduced, because there is insufficient response to the lower tones. In practice these conditions should be adjusted to meet the requirements of the particular purpose for which the instrument is to be used.

The magnetic effects of the parts may be varied by a change in the shape or the strength of the magnet; in the thickness or diameter of the diaphragm, and in the length of air gap between the pole piece and the diaphragm. The change in the shape or in the degree of magnetization of the core, if such modifications are made at all, would naturally be in the direction of an increase in the flow of force between the pole and the diaphragm. The advantage from such a change, considering the core alone, would be limited by the approach of the core to saturation; but practically, as we have seen, this point can never be reached, because the saturation point of the diaphragm occurs at a very much lower strength of field. The proper strength of field to use, therefore, for the best effect, depends upon the magnetic mass of the diaphragm and the length of air gap. With a large, thick diaphragm or a long air gap, there can be used to advantage a correspondingly stronger field than in cases in which any or all of these other quantities have smaller values. The limit to the strength of field is set, in every practical case, by the dimensions and distance of the diaphragm, and any attempts to modify the instrument by the use of a strong magnet or by a change in shape of the magnet resulting in a magnetic field of more than moderate strength, are likely to prove worse than useless.

To increase the sensitiveness of a receiver, then, we may use a thinner diaphragm or place it nearer the pole, or do both. A thin diaphragm, because of its small mass and relatively low rigidity, responds more readily and offers less resistance to pull than a thick one. Its motion, for a given change in pull upon it, will be greater as it is nearer the pole, but if placed too near it will be pulled into contact, either violently, by the action of the line current, or slowly, by the action of the magnet when the receiver is not in use. Moreover, a certain constancy of relation must be maintained between the thickness and diameter of the diaphragm. For successful operation, a thick diaphragm must be correspondingly larger than a thin one.

The adjustment of the proportions of the receiver to the conditions of use would lead us to make it as sensitive as possible when the transmitter is inefficient or when the current is much weakened by the properties of a long or a poor line. The disadvantages of a weak transmitter are too obvious to need pointing out; and the chief objection to a very sensitive receiver is that it reproduces any disturbances which the line may have taken up as faithfully as it does the sound from the transmitting end. A very sensitive receiver would, therefore, be unsuitable for use on a grounded line or on a metallic circuit of poor design and construction; while on a long metallic circuit in good condition the simple weakening of the transmitter current might be, to some extent, compensated by using a sensitive and delicate receiver. For ordinary exchange service great sensitiveness is undesirable. The magnet should, therefore, be not very strong, the diaphragm moderately thin and placed at a short but entirely safe distance from the pole. These conditions are well exemplified in the ordinary "hand telephone," in which the diaphragm is 0.01 inch thick, 2¼ inches in diameter, and the air gap $\frac{1}{32}$ inch. The magnet will sustain a weight of about one pound.

The extreme of power without much sensitiveness is shown in the police transmitter. The police transmitter has a large and correspondingly thick diaphragm in a strong magnetic field. The magnet is of the horse-shoe form, presenting both poles to the



central portion of the diaphragm. Each pole piece is elongated and is surrounded by an elliptical coil, as in the Siemens receiver. In the original design, the diaphragm was "buckled" by the clamping device. This gave somewhat greater power than a flat diaphragm, but the arrangement was found not to be practical, as the diaphragm was soon drawn against the poles and held there. Very characteristic differences are to be observed in the operation of two instruments, contrasting in their design, such as the police telephone, with its large, thick diaphragm and strong magnet, and a small receiver having a small, thin diaphragm and a relatively weak magnet. The large, thick diaphragm gives, with the strong magnet, a loud but somewhat muffled sound, with little or none of the crisp and clear articulation of the thin diaphragm; while with the latter the presence of the higher overtones in perhaps undue proportion is evident in an apparent rise in pitch and a characteristic quality not easy to describe, inclining toward a shrill hoarseness, but without the unpleasant effect which would be implied by that term.

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