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Presented at the 348th Meeting of the American Institute of Electrical Engineers, Boston, Mass., March 14, 1919.

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THE ABSOLUTE MEASUREMENT OF THE INTENSITY OF SOUND

BY ARTHUR GORDON WEBSTER

ABSTRACT OF PAPER

This paper includes a description of a series of acoustical researches extending over a period of twenty-eight years. The properties of vibrating bodies and the subject of elastic hysteresis are discussed. Two fundamentally important instruments for the absolute measurement of sound have been developed and the theory given. The first is the standard of sound, called the phone, which is capable of reproducing at any time a sound of the simplest character and which permits the output of sound to be measured in watts of energy. The second is an instrument called the phonometer for measuring a sound in absolute measure. This instrument is now practically as sensitive as the human ear. Two essential features are the small damping of the vibrating system which results in extreme sensitiveness, but at the same time in great selectiveness, and the capacity for being tuned. Each of these instruments is fitted with a variable volume resonator and tuning over a range of about two octaves is accomplished by varying the volume of the resonator and by changing the tension of the wires to which the piston is attached. The determination of the space distribution of sound and of the effect of disturbing bodies, and the measurement of the reflecting coefficient of surfaces have been accomplished. The phonotrope is a third instrument designed and used to find the direction of a source of sound, for example a fog signal.

THE profession of acoustical engineering is a new one that has arisen during the last few years. The late Professor Wallace C. Sabine, of Harvard University, attracted the attention of the public to the very great importance of physical measurement and thoroughly scientific design in the construction of auditoriums which until his time had remained an entire mystery to architects.

The writer has been interested for many years in the problem of the measurement of sound in absolute units, involving the design of an instrument which is capable of determining, at any point in space, the pressure in the air wave as a function of the time. In order to carry out this object three things are necessary.

First, the construction of a standard of sound which will enable a given sound of the simplest possible character, namely,

that in which the pressure varies as a simple harmonic function of the time, to be reproduced at any time, and which permits an output of sound to be measured in watts of energy. This problem has been solved by a number of persons including Professor Ernst Mach and Dr. A. Zernov of Petrograd.

Second, the invention of an instrument capable of measuring a sound of the simple harmonic character described, also in absolute measure; that is to say, in such a way that the amplitude of pressure variation may be measured in absolute measure, as dynes per square centimeter, or in millionths of an atmosphere. This problem has also been successfully treated by a number of investigators, among whom may be mentioned Professor Max Wien, Lord Rayleigh and Lebedeff.

Third, a step in the process remains which is perhaps equally important as the first and second. Given the invention of the proper source of sound, which I have called a phone, because it is a sound and nothing else, and a proper measuring instrument, which I call a phonometer, there still remains the question of the propagation and the distribution of sound in space between the phone and the phonometer. Any measurements made in an enclosed space will be influenced by the reflection from the walls, and even if we had a room of perfectly simple geometrical form and were able to make the instruments of emission and reception work automatically without the disturbing presence of an observer, it would still be impossible to specify the reflecting power of the walls without a very great amount of experimentation and complicated theory. Nevertheless, this is exactly what Sabine did. He did it, however, by employing as a receiving instrument the human ear. Those who have made experiments upon the sensitiveness of the human ear for a standard sound will immediately doubt the possibility of making precise measurements by the same ear at different times, and particularly of comparing the measurements made by one ear with those made by another. Nevertheless, Sabine attained wonderful success and was able to impart his method to pupils and colleagues who carried on his methods successfully.

To proceed with the question of disturbing objects, one should take his phone and his phonometer to an infinite distance from all objects, which is manifestly impossible. The plan which I followed was to attempt to get rid of all objects except an infinite space covered with a surface the reflecting coefficient

of which could be measured. I found the proper weather and the proper space on the golf links of a country club where conditions appeared to be favorable. Several days were spent in determining the reflection coefficient. This was done about ten years ago, whereas with the instrument available to-day it could be done in a very few minutes.

The history of my investigations is briefly as follows: In 1890 I proposed to use a diaphragm made of paper or some similar substance which should be placed, shielded on one side, at the spot where the sound was to be measured. Upon the center of the diaphragm was cemented a small plane mirror. In close juxtaposition and parallel with this was the plane side of a plano-convex lens which viewed in the light from a sodium flame was to give Newton's rings, or as we now call them, interference fringes. Of course, when the sound falls upon the diaphragm, the fringes vibrate rapidly and disappear from sight. I then determined to use a stroboscopic arrangement which would permit the viewing of the fringes as they slowly shifted their position. All sorts of difficulties occurred. The light from the sodium flame was not strong enough to permit the fringes to be seen through the stroboscopic device. It was not at that time easy or perhaps possible to make an electric motor that should drive a stroboscopic disk at a constant speed. One of the first difficulties was to devise a method of controlling a synchronous motor. This was accomplished by means of interrupting the current by a tuning fork.

Later I made the acquaintance of Professor A. A. Michelson and of his remarkable optical interferometer, and I immediately saw that one of the difficulties which I had met, namely, the difficulty of adjustment of the lens so that it should not strike the vibrating plate, could be overcome at once, as the two mirrors in the Michelson interferometer could be any distance apart. Also the trouble due to the faintness of the light disappeared, for in Michelson's instrument white light could be used, and it was possible to use gas, incandescent or arc light with good effect.

In 1896 I put the subject in the hands of a student who produced an instrument which was successful. The examination of the substance suitable for a membrane or a diaphragm consumed much time, and all organic substances such as parchment, paper or anything of that sort had to be discarded because it was impossible to keep the tension constant under

the changes of moisture in the air. Metal was found to be quite out of the question on account of the difficulties due to thermal expansion. We next decided upon thin glass diaphragms which we afterward found were used by phonograph companies. A slight change of temperature, however, such as was made by breathing upon the diaphragm, would sometimes produce a change of pitch of several tones, so I next decided to clamp the glass diaphragm upon a ring sawed out of plate glass and cement it on with silicate of soda. I finally found that it was possible to get mica so flat that it was superior to the best possible glass, and this gave me the best results up to that time.

Let me now state briefly the qualities which the diaphragm must have in order to be successful. It is well known to physicists that a flat diaphragm can vibrate in an infinite number of modes which the physicist calls normal vibrations. In the simplest mode the diaphragm vibrates so that every point moves in the same direction. The natural period of this vibration is the lowest that the diaphragm can have. Next is a mode in which the central portions of the membrane move in one direction while all those outside of a certain circle, which we call a nodal line, move in the opposite direction. Other vibrations have radial, as well as circular, nodal lines on the opposite sides of which the diaphragm is moving in opposite directions. When a mass is screwed to any point of the diaphragm its motion is entirely changed. And any apparatus that may be attached to the diaphragm and required to do work, such as the carbon button of the telephone, or anything that interferes with the free response of the diaphragm to the variations of the air pressure will alter the action in such a way as to make it extremely difficult of interpretation. My idea, then, was to make a diaphragm which did not do any work at all, but merely carried the mirror which moved practically by itself.

Now, in spite of the great variety of forms and vibrations, it can easily be shown that under proper circumstances the diaphragm will move essentially as a whole, and may, therefore, be compared to a single body which has three characteristic constants: First, its mass; second, its stiffness, defined as the force required to produce a unit deflection of its central point; and third, and most difficult to control, the coefficient of damping, which is defined as the force of resistance that will be

exerted from any cause when the velocity of the body or the central point of the diaphragm is unity. This damping must be due to a large number of causes. In the first place, the resistance of the air will cause damping. In the second place the energy of the sound waves that are radiated from the vibrating diaphragm will cause damping. In the third place and by far the most important, the bending of any body is resisted by elastic forces and we therefore have the phenomenon of elastic fatigue. In order to settle the question "what is the best material from which to make tuning forks", which has been variously answered as tool steel, bronze, bell metal, quartz, etc., I perceived that it was necessary to have an exact method of experimentation.

In striking a steel bar supported by a string at two points it will be observed that the high overtones emitted by the bar rapidly die away, and it occurred to me that if the bar were thrown into one normal vibration there would be a rate of damping for every normal vibration, and that by stating the rate of natural damping the elastic hysteresis could be studied. This was demonstrated experimentally by my assistant Mr. James L. Porter with very successful results as far as the experiment went. The mathematical theory has been lacking up to the present time. Two theories are possible, first the theory of solid viscosity, and second the theory of heredity, or elastic hysteresis. The attempts to compute the results of our experimental measurements are now approaching completion, and we soon shall be able to give a theory of elastic hysteresis. My conclusion is that fused quartz is the best substance from which to make tuning forks.

This digression from the investigation is made in order to show the very great difficulties that this subject presented.

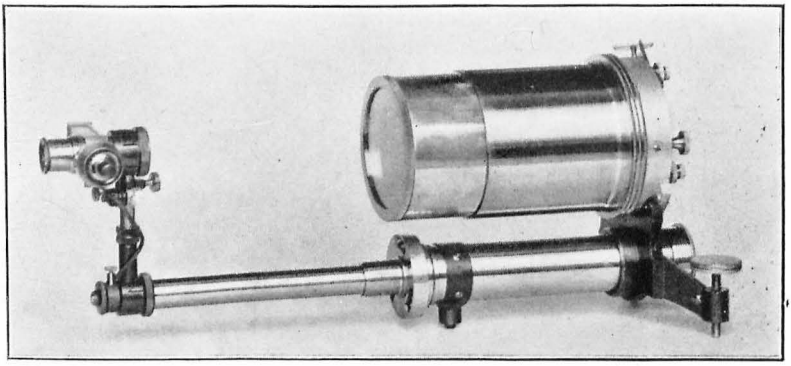
The illustrations (shown in the] lecture, but [not] reproduced) show the apparatus as it was built several years ago. It was mounted upon a heavy stand made of bronze, covered in at the back by a heavy bronze cover, through which protruded through air-tight fittings the shafts turning the screws of the interferometer adjustments, three in number. Upon the front of the instrument was attached a resonator properly tuned and at the side was a small incandescent lamp with a straight filament arranged horizontally, an image of which was projected by a lens upon the first miror of the interferometer. A telescope was focused

upon this image, giving an image in the reticule of the horizontal straight filament. This was crossed by the vertical interference fringes. The objective of the telescope was carried by one prong of a tuning fork which oscillated vertically and this, combined with the horizontal oscillation of the fringes due to the vibration of the diaphragm, resulted in a figure in the form of an ellipse. On tuning the two sounds nearly together this ellipse could be caused to go through its various phases as slowly as desired. At the moment when the ellipse degenerated into an inclined straight line the reticule, which was tilted by an observer, was brought into line with the interference band and the tangent of the angle was read off on a straight scale. The pressure in the sound wave was then proportional to the number read off on the tangent scale. The apparatus was used in this form for a good many years, a precursor of it being shown at the Congress of Physics at Paris in 1900.

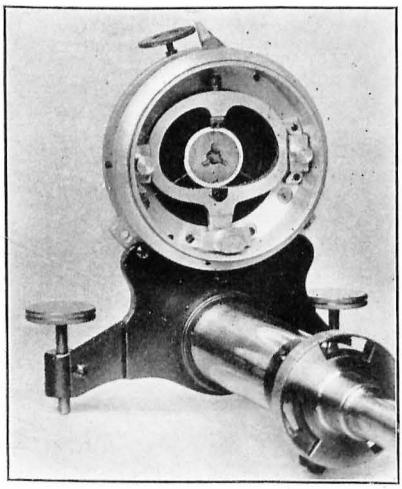
Professor D. C. Miller's phonodeik, which is a very beautiful instrument, was designed for quite other purposes than the phonometer of the speaker. It was intended to photograph sound curves of any sort and by means of it Professor Miller has obtained most beautiful reproductions of speech, and sounds of musical instruments. Unfortunately, this instrument does not adapt itself in the least to absolute measurements. One objection to Professor Miller's instrument is that it employs a spring made of rubber material. This spring has to be calibrated whenever measurements are taken, and it is well known that the properties of soft rubber are far from constant.

The speaker next undertook to devise a better mode of reading the amplitude of vibration of his diaphragm. In the first place, the mirror which was rotated by the diaphragm in Professor Miller's apparatus, instead of being carried on an axis in jewels was placed on a thin steel torsion strip which could be made at far less expense and could be rapidly adjusted. The straight filament lamp was now viewed through a telescope into which the mirror focused the filament in the reticule of the eyepiece. A magnification of about 1200 to 1500 is used. The instrument was also used photographically just as the old instrument had been used to photograph the motion of the interference fringes. Photographing moving interference fringes, however, was attended by many experimental difficulties.

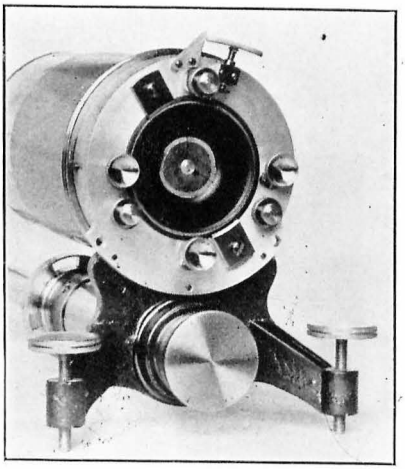
A new instrument in the form described was made in 1913, for



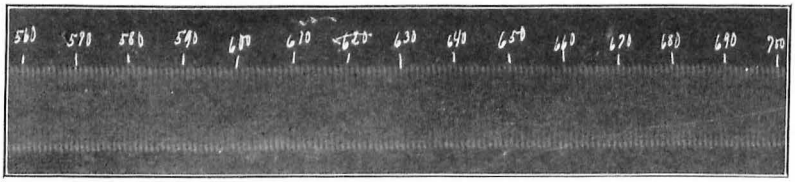
PHONOMETER



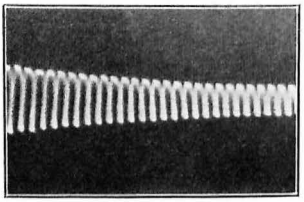
PHONOMETER—INTERIOR



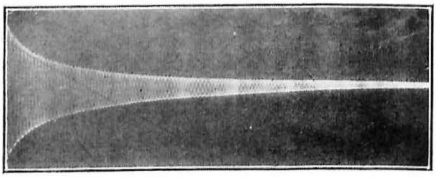
[WEBSTER]
PHONOMETER—FRONT VIEW



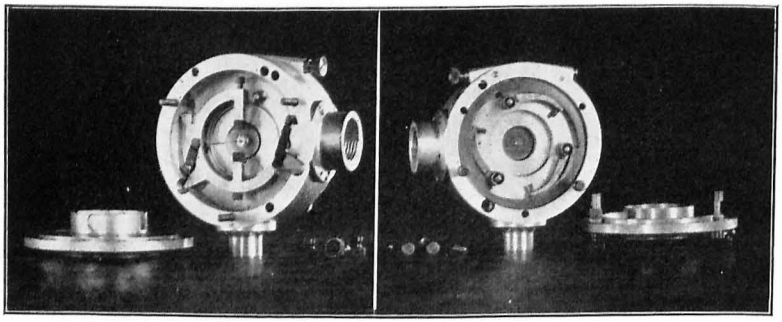
QUARTZ TUNING FORK



DAMPING OF QUARTZ TUBE



DAMPING OF PHONOMETER



[WEBSTER]

PHONOTROPE

PHONOTROPE—TUNING DEVICE

Professor Louis Vessot King,* of McGill University, who had a commission from the Canadian Government to make experiments upon fog signals and had secured permission to investigate the great siren at Father Point on the St. Lawrence. Professor King spent the whole summer at Father Point in making the first survey of an acoustical field ever made. The Canadian Government had furnished him a large steamer with which he went out every day, blew the "criard" as the natives call it, the very perfect siren which can be heard thirty miles away in good weather, and explored the gradient of sound under all meterological conditions, studying the wind, the temperature of the air and of the water, etc. This spurred the speaker on to undertaking the same thing in this country. It was impossible to get from the Lighthouse Board the loan of a steamer, but permission was given to go on any lighthouse steamer going along the coast of Maine. The first step was to tune the phonometer for the different pitches, and at that time the only method of tuning the diaphragm was to load upon it small pieces of wax. This, although it worked perfectly, seemed very clumsy, and not an engineering method. It was therefore decided to redesign the whole instrument so that it could be tuned continuously. It occurred to me that this could be accomplished by furnishing potential energy to the diaphragm by means of a string parallel to it, and bearing against it by means of a bridge, and tunable like a violin string. The very first attempt showed this to be entirely successful. Then the idea immediately presented itself that if a string could be tuned continuously why use the energy of bending at all and why not get entirely rid of all difficulties of elastic fatigue. Since that time the diaphragm has been entirely discarded and replaced by a stiff disk supported upon three strings in tension. The disk is made of aluminum or mica and is carried by a little spider made of aluminum containing three clamps to hold the wire. The wire is made of steel and is under tension about steel pegs, two of which are turned roughly by means of a screw driver, the other by means of a lever actuated by a micrometer screw. We have now a very perfect instrument at least ten times as good as the one Professor King had.

A few figures will show the advantages in the reduction of the damping. In a system of one degree of freedom the ampli-

*King, Phil. Trans. Ser. A. Vol. 210, pp. 211-293-1919.

tude of the vibration for the most perfect tuning is inversely proportional to the quotient of the damping coefficient k divided by the mass m. When we began with the good glass diaphragm we had a value of k something like 150. In 1913 the mica diaphragm lent to King had reduced this to 30. With the phonometer as built now we have reduced this to 1.34. In all these cases the mass was about the same so that so far as the sensitiveness goes, the instrument is more than one hundred times as good as it was ten years ago. The instrument now competes in sensitiveness with the human ear and may be tuned to pitches varying by perhaps two octaves. If I strike a tuning fork and allow its amplitude to die away, a person looking into the eye-piece of the instrument cannot say with certainty whether he can see the sound or hear it the longest. Unfortunately, however, this very great sensitiveness obtained by a small damping is attended with a very great disadvantage. The instrument is extremely selective and if the tuning varies by a very small amount the amplitude falls off very greatly.

Within the last three months I have devised a plan of doing away with this, and making an artifcial ear. For, as you know, the human ear has a wonderful sensitiveness, not for all sounds, but to sounds of a frequency of perhaps 30 per second up to perhaps 30,000 per second, attaining a maximum sensitiveness for frequencies of from 1000 to 1500. We know how this affects the telephone and how the damping of the telephone and microphone disks enables the response to be carried over a large range, so that they answer very well for the frequencies involved in speech. Nevertheless, the sounds of s, f, t, and certain others, on account of the very high harmonics involved, are most difficult to transmit telephonically.

Having described the construction of the diaphragm, the new piston with wires, and the method of reading the vibration by means of the inclined mirror which is also reduced to absolute measure by means of the interferometer temporarily attached, or more simply by displacing the diaphragm by a micrometer screw, I come to the theory of the instrument. The resonator into which the air enters, and the hole which is now constituted by an annular opening around the disk, furnishes through the movement of the air in and out an additional degree of freedom. We are then in the possession of a system with two degrees of freedom, statically coupled by means of the increased pressure

in the resonator when the piston is forced in. The theory of such a system under the action of the periodic force is well known and has been treated by Professor Max Wien in great detail. If the frequency in 2 π seconds be n and if the mass be m, I shall call the stiffness minus the product of the mass and square of the frequency the uncompensated stiffness or mistuning. If this were equal to zero for a system of one degree of freedom we should have resonance. In the case of two degrees of freedom I plot the mistunings horizontally and vertically, and the amplitude of response as a third co-ordinate. I thus get a surface that may be described as two mountain peaks with a pass between them, the summit of the pass being when both mistunings are zero; but this is by no means the highest point of the region. To attain either summit we must mistune both systems by a certain amount which is porportional to their two dampings. The addition of the resonator to this instrument may produce an increase of sensitiveness of fifty times. You now see, I hope, how we have obtained an engineering instrument, everything in which is measurable in absolute measure. It is obvious that the piston may be made the diaphragm of the telephone, that the instrument may be used by the psychologist, the engineer, the physiologist, for instance in a stethoscope, and in many other applications.

I turn now to the source of the sound, the phone. With the advent of the tuneable diaphragm came the new phone. It is very light. The amplitude of the diaphragm is measured by a microscope. I use a hot wire vacuum tube as a source of alternating current, tuneable at will, and tune the phone to it. We thus have in small compass a very perfect set of acoustical instruments.

The third portion of my investigations involved a determination of the coefficient of reflection of the ground. In order to accomplish this the phone is set at a convenient height and the phonometer at a convenient distance. The latter is then moved back and forth at the same height, when it is immediately found that interference between the phone and its image in the ground sets in, producing a variation of the intensity of the sound. Different curves have been plotted for different coefficients of reflection. When the reflection is zero or the ground is acoustically perfectly black we have a rectangular hyperbola. The existence of the minimum is obvious to the most unskilled observer. We found the coefficient of reflection of grass, or gravel surface, to be about 95 per cent. I

may say that the whole measurement of the instruments of the two ends and the transmission between checks up with an accuracy of probably better than two per cent. With this apparatus all sorts of experiments have been performed. By attaching to the phonometer a long glass tube or antenna it has been made possible to explore all sorts of places, such as the field within a horn or a tube lined with absorbent substance. The theory has been always completely verified. In order to examine the transmission of sound a piece of substance is clamped between two heavy cast iron rings cemented against a hole in a brick wall which will exclude all sound except that that comes through the fabric. The transmission through doors, windows, walls, and telephone booths may be carried out very quickly, and the coefficients of absorption and reflection determined.

Finally, there has resulted an instrument for determining the direction of a fog signal blowing in the fog which I call a phonotrope; since the heliotrope turns toward the sun, the radiant of heat, so the phonotrope turns toward the radiant of sound. This instrument consists of two equal horns bringing the sound to the opposite side of the same disk. It is arranged to be rapidly tuned to the whistle, and when the whistle blows the band of light spreads out; the whole instrument is then revolved until the band reduces its width to zero when the whistle is directly ahead. This instrument was taken to Pensacola to see whether it would determine the direction of an aeroplane in the night. It was found to be as sensitive as the ear, but owing to Doppler's principle, the continual coming and going of the aeroplane changed the pitch so as to put it out of tune. A new modification that I have devised will obviate this I hope.

I have now given you briefly and without any mathematics an account of the principles which I think must always be involved in any measurements of sound. I have always been very anxious to join forces with Professor Miller and to calibrate his instruments so as to render his wonderful results of serious interest to the physicist. I am also glad to co-operate with all my colleagues whether engineers, physicists, physiologists or physicians. It will be a great pleasure to me to know that this apparatus may be of use in solving any of the multitude of questions that confront us.

The plates annexed clearly show the three instruments and several damping curves.

The following list of papers *read* is annexed. Only those marked with an asterisk have been printed, except in abstract.

PAPERS ON SOUND

1. B. A. A. S. Toronto, Aug. 1897. "A New Instrument for Measuring the Intensity of Sound".

2. A. A. A. S. Boston, Aug. 1898. "A New Instrument for the Measurement of the Intensity of Sound".

3. A. A. A. S. Washington, Jan. 1903. "A Portable Apparatus for the Measurement of Sound".

4. American Phys. Soc., New York, April 1902. "An Apparatus for the Quantitive Study of Sound."

5. Am. Phys. Soc., New York, April 1902. "Vibrations of Rotating Wires, Spindles and Shafting."

6. Nat. Acad. Sciences, Boston, Nov. 1906. "Acoustic Measurements".

7. Nat. Acad. Sci., New York, Nov. 1907. "Rayleigh's Disk as an Absolute Measure of Sound".

8. Am. Acad. Arts & Sci., Boston, May 1908. "Absolute Measurements of Sound".

9. Am. Phys. Soc., New York, Oct. 1908. "Distribution of Sound from the Megaphone".

10. National Acad. Sci., Washington, April 1910. "On the Distribution of Sound from the Megaphone or Speaking Trumpet".

11. Nat. Acad. Sci., Washington, April 1910. "A New Method for the Study of Elastic Hysteresis."

12. B. A. A. S., Sheffield, Aug. 1910. "A Complete Apparatus for the Measurement of Sound".

13. Am. Phys. Soc., Washington, Dec. 1911. "Elastic Hysteresis in Metal Bars".

14. Am. Phys. Soc., Washington, Dec. 1911. "Another Instrument for Photographing Sound".

*15. Am. Acad. Arts & Sciences, Dec. 1910. "The Wave Potential of a Circular Line of Sources".

16. Am. Math. Soc., Poughkeepsie, Sept. 1911. "The Wave Potential of a Circular Line of Sources".

17. Am. Phys. Soc., Cleveland, Jan. 1913. "Some Points Concerning Absolute Measurements in Sound".

18. Am. Phys. Soc., New Haven, March 1913. "Forced Vibration of a Circular Plate".

19. Nat. Acad. Sci., Baltimore, Nov. 1913. "A New Portable Phonometer".

20. Nat. Acad. Aci., Baltimore, Nov. 1913. "The Transmission of Sound Through Porous Materials".

21. Am. Phil. Soc., Philadelphia, April 1913. "Some Observations of the Transmission of Sound Through Walls."

22. Am. Physical Soc., Washington, April 1914. "A New Phonometer".

23. Am. Phys. Soc., Philadelphia, Dec. 1914. "A New Standard Phone and Phonometer for any Pitch".

24. Nat. Acad. Sci., New York, Nov. 1915. "Experiments and Theory of Conical Horns".

25. Nat. Acad. Sci., New York, Nov. 1915. "Instruments for the Measurement of Sound".

26. Nat. Acad. Sci., New York, Nov. 1915. "An Instrument for Finding the Direction of a Fog-Signal".

*27. Am. Phys. Soc., Columbus, Dec. 1915. "Mechanical and Acoustical Impedance, and the Theory of the Phonograph".

28. Am. Phys. Soc., Columbus, 1915. "Impedance of Conical Horns".

29. Am. Phys. Soc., Columbus, Dec. 1915. "The Phonotrope, a new Instrument for Finding the Direction of an Acoustical Ray".

*30. Am. Math. Soc., Cambridge, Sept. 1916. "On Acoustical Impedance, and a Theory of Horns".

31. Am. Acad. of Arts and Sci., Boston, Nov. 1916. "Practical Tests of a New Phonotrope".

32. Nat. Acad. Sci., Baltimore, Nov. 1918. "An Automatically Played Brass Instrument".

33. Am. Phys. Soc., Baltimore, Dec. 1918. "A Mechanically Blown Wind Instrument".

DISCUSSION ON "ELECTROMAGNETIC THEORY OF THE TELEPHONE RECEIVER" (KENNELLY AND NUKIYAMA) AND "ON THE ABSOLUTE MEASUREMENT OF THE INTENSITY OF SOUND" (WEBSTER). BOSTON, MASS., MARCH 14, 1919.

John B. Taylor: Certainly the matter of tone that Prof. Webster spoke of, the acoustical analysis of musical instruments, is intensely interesting. We have been trying to discover why a bassoon, which is a very complicated instrument, is absolutely unwritten up in a technical way. It is very gratifying to hear Prof. Webster say that he can measure these sounds and noises in quantitative terms.

If Prof. Webster had been at the last meeting of the Institute in New York City, when there was a discussion on telephone interference, and this new interference standard, after all, is a matter of noise, going into the Institute Standardization Rules, he would have been able to contribute something instructive. A question was asked at the meeting about the quantitative measuring of noise in the telephone field, and I do not recall that the answer to that question was very illuminating.

T. E. Shea: According to Dr. Kennelly's theory, I believe, the action of a telephone receiver may be likened somewhat to that of a single-phase transformer, except that the secondary circuit generates oscillating mechanical power instead of oscillating electrical power. The authors of the paper have, in effect, combined the equivalent vector diagrams of the mechanical circuits with the vector diagrams of the electrical circuit; and the resulting diagrams they have obtained are similar to those ordinarily used in explaining the theory of the transformer.

But the wide range of frequencies considered has introduced several new elements, regarding which the authors have made assumptions. One of these assumptions is that the current passing through the receiver is constant. Another is that the angle of lag of the flux behind the impressed magnetomotive force, called by Dr. Kennelly the hysteretic angle β, is also constant.

I would like to ask Dr. Kennelly if, when the current through the receiver varies over a wide range, as it does in practise, the hysteretic angle β would not also vary greatly. I realize that Dr. Kennelly has not attempted to push his theory beyond the limits of constant current, but I think the impression has been given that the angle β is independent of the other variables of telephone receiver theory.

B. A. Behrend: I wish to call attention to the fact that the term "motional impedance" was first suggested by our honorary member, Mr. Oliver Heaviside, to whom we also owe the terms "inductance", "reactance", and "impedance".

R. L. Jones: Professor Webster has described and shown three exquisitely designed acoustical instruments which should be very serviceable in certain types of sound researches. Both

the phone and the phonometer are characterized by very sharp tuning, however, and although tunable, an appreciable period of manipulation is required to adjust precisely to a new pitch. In much work, as for example in many studies of speech and music, we are interested in a whole range of frequencies or a flow of rapidly changing pitch. In such cases we need a sensitive phonometer of uniform frequency characteristics. Such apparatus is provided by a properly designed and calibrated combination of electrostatic telephone transmitter and vacuum tube amplifier, as has been described in recent volumes of the *Physical Review*.

The paper by Professor Kennelly and Mr. Nukiyama is primarily a pictorial treatment of the electric and magnetic relations of the telephone system by means of vector diagrams. I believe it will broaden the consideration if we discuss the matter algebraically for the case of a relatively simple receiver.

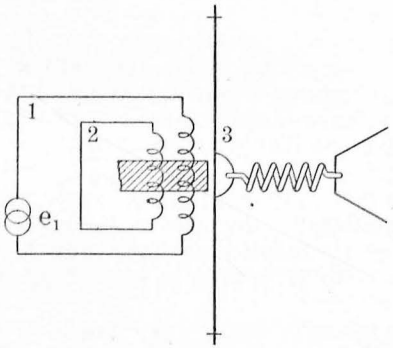


FIG. 1—SIMPLE RECEIVER WITH EDDY CURRENTS IN THE CORE

Let us assume that straight line laws hold and in general make the other usual simplifying assumptions just as the authors do. In addition assume that for the frequencies under consideration hysteresis is negligible compared to eddy current losses and that the eddy current losses in the diaphragm are negligible compared to those in the cores. From experience these assumptions appear reasonable as a first approximation.

Fig. 1 then shows the condition schematically where 1 is the driving circuit, 2 the schematic equivalent of eddy current circuits in the cores, and 3 the mechanical or diaphragm circuit. The following nomenclature will be used:

a = inductance or mass
b = resistance, electrical or frictional
c = stiffness
Z = impedance, electrical or mechanical
$\dot{x}$ = current or velocity

Subscripts refer to the networks of the coupled system, 1 the driving circuit, 2 the eddy current circuit, and 3 the diaphragm or mechanical circuit.

Then from the figure we may write down the well known force equations. There is an electromotive force, e_1, let us say, working in the driving circuit, none in the eddy current circuit, and no external forces working on the diaphragm.

$$\begin{aligned} e_1 &= Z_{11}\dot{x}_1 + Z_{12}\dot{x}_2 + Z_{13}\dot{x}_3 \\ 0 &= Z_{21}\dot{x}_1 + Z_{22}\dot{x}_2 + Z_{23}\dot{x}_3 \\ 0 &= Z_{31}\dot{x}_1 + Z_{32}\dot{x}_2 + Z_{33}\dot{x}_3. \end{aligned} \qquad (1)$$

The relations of the mutual impedances appearing in these equations are as follows:

Z_{12} and Z_{21} are the mutual impedances between the driving and eddy circuits

Z_{13} and Z_{31} are the force and reaction factors between the the driving circuit and the diaphragm

Z_{23} and Z_{32} are the force and reaction factors between the eddy circuit and the diaphragm

$$\begin{aligned} Z_{12} &= Z_{21} \\ Z_{13} &= -Z_{31} \\ Z_{23} &= -Z_{32}. \end{aligned} \qquad (2)$$

The mutual impedances of a transformer are of the same sign since flux due to current in either winding is opposed by that due to induced current in the other winding. In considering the mutual relations between the receiver diaphragm and either the driving or eddy current circuits, however, it is seen that whereas flux due to diaphragm motion induces currents which set up an opposing flux, flux due to current in the driving winding produces a motion of the diaphragm which tends to increase the flux still further. Hence in the receiver the force and reaction factors are of opposite sign.

By means of (**1**) and (**2**)

$$Z_1 = \frac{e_1}{\dot{x}_1} = Z_{11} - \frac{2\,Z_{12}\,Z_{13}\,Z_{23} + Z_{12}^2\,Z_{33} - Z_{13}^2\,Z_{22}}{Z_{22}\,Z_{33} + Z_{23}^2} \qquad (3)$$

If the diaphragm is damped so that $\dot{x}_3 = 0$, then from (**1**) and (**2**)

$$Z_{1d} = Z_{11} - \frac{Z_{12}^2}{Z_{22}}. \qquad (4)$$

By subtraction the motional impedance of the receiver,

$$Z_{1m} = \frac{\left(Z_{13} - Z_{23}\dfrac{Z_{12}}{Z_{22}}\right)^2}{Z_{33} + Z_{23}\dfrac{Z_{23}}{Z_{22}}}. \qquad (5)$$

If there were no eddy currents this would reduce to

$$Z_{1m}' = \frac{Z_{13}^2}{Z_{33}} . \tag{6}$$

the form familiar to us as the square of the force factor divided by the mechanical impedance of the diaphragm. Comparing (5) we see that the force factor with eddy currents has the value

$$B_{13} = Z_{13} - Z_{23}\frac{Z_{12}}{Z_{22}} = b_{13} - b_{23}\frac{j\,\omega\,a_{12}}{b_2 + j\,\omega\,a_2} \tag{7}$$

$$= \left(b_{13} - b_{23}\cdot\frac{\omega^2\,a_{12}\,a_2}{b_2^2 + \omega^2\,a_2^2}\right) + j\,b_{23}\cdot\frac{\omega\,a_{12}\,b_2}{b_2^2 + \omega^2\,a_2^2} \tag{8}$$

The effect of eddy currents is evidently to decrease the force factor with increasing frequency, and to cause a lag.

Substituting B_{13} in (5),

$$Z_{1m} = \frac{B_{13}^2}{Z_{33} + Z_{23}\dfrac{Z_{23}}{Z_{22}}} . \tag{9}$$

Substituting primary constants for Z's it may be seen that Z_{1m}

$$= \frac{B_{13}^2}{\left[b_3 + \dfrac{b_2\,b_{23}^2}{b_2^2 + \omega^2\,a_2^2}\right] + j\left[\omega\left(a_3 - \dfrac{a_2\,b_{23}^2}{b_2^2 + \omega^2\,a_2^2}\right) - \dfrac{c_3}{\omega}\right]} \tag{10}$$

Centering attention on the denominator it may be seen that the eddy current may be considered as increasing the mechanical resistance by an amount equal to

$$b_2\cdot\frac{b_{23}^2}{|Z_2^2|} .$$

Similarly it may be considered as decreasing the effective mass by an amount

$$a_2\cdot\frac{b_{23}^2}{|Z_2^2|} .$$

or as increasing the elasticity by a corresponding factor. Physically this second factor merely changes the apparent mechanical reactance.

Now let us turn to a consideration of efficiency relations in the simple receiver with eddy currents in the core. Writing down the power output of the diaphragm divided by the power input to the driving winding we have

$$\mu_{13} = \frac{|\,\mathring{x}_3^2\,|\,.\,b_3}{|\,\mathring{x}_1^2\,|\,.\,B_1} \tag{11}$$

where B_1 is the apparent or free resistance of the driving circuit.

Solving for $\frac{\mathring{x}_3}{\mathring{x}_1}$ from (**1**) and substituting we have

$$\mu_{13} = \frac{\left|\left(Z_{13} - Z_{23}\frac{Z_{12}}{Z_{22}}\right)^2\right|\,.\,b_3}{\left|\left(Z_{33} + Z_{23}\frac{Z_{23}}{Z_{22}}\right)^2\right|\,.\,B_1} \tag{12}$$

By further substitution from (**5**) and (**7**)

$$\mu_{13} = \frac{|\,Z_{1m}^2\,|}{\frac{|\,B_{13}^2\,|}{b_3}\,.\,B_1} \tag{13}$$

This expression is the true overall efficiency of the receiver at any frequency in terms of the motional impedance, the free resistance, the force factor and the mechanical resistance. If we multiply this last expression by the ratio of the apparent mechanical resistance (**10**) to its true value, we get

$$\mu_{13}' = \frac{|\,Z_{1m}^2\,|}{\frac{|\,B_{13}^2\,|}{b_3 + b_2\frac{b_{23}^2}{|\,Z_2^2\,|}}\,.\,B_1} = \frac{|\,Z_{1m}^2\,|}{|\,Z_{1m/0}\,|\,.\,B_1} \tag{14}$$

Since the first factor of the denominator, the ratio of the square of the force factor to the apparent mechanical resistance, is the motional impedance at resonance, at resonance this reduces to

$$\mu_{13/0}' = \frac{|\,Z_{1m/0}\,|}{B_1} \tag{15}$$

This is what Dr. Kennelly calls the "gross efficiency at apparent resonance." It is very readily determined from the motional impedance diagram, and is susceptible of fairly precise determination. On the other hand, it applies simply to a single frequency, and is a value that, for the comparison of different receivers, is generally applicable only in case the receivers are quite similar in their natural frequencies and ranges of response. In the case of telephones for wireless telegraphy, one is interested in response at substantially a single frequency and for such instruments this apparent efficiency taken in conjunction with the natural frequency gives a very good measure of the relative performance of different types. It may be of interest to note that for nearly a year past the U. S. Signal Corps specification for wireless telephones has had a requirement

stated in terms of these quantities. In the telephone problem, however, we are interested in the whole range of speech frequencies running from 200 or 300 cycles up to 3000 or above. In receivers for reproducing speech, therefore, whether transmitted by wire or by radio, we cannot depend upon the relative measures given by expression (**15**), but must apply (**13**) to the whole range of frequencies, or get some other equivalent measure.

To retransform μ_{13}' to μ_{13}, we have to multiply by the ratio of the true mechanical resistance to the apparent value. The latter appears in the denominator of (**10**). This ratio,

$$\eta = \frac{b_3}{b_3 + b_2 \dfrac{b_{23}^2}{|Z_2^2|}} \qquad (16)$$

as pointed out by Dr. Kennelly, measures the vibratory efficiency of the diaphragm, showing the fractional part of the total vibratory power that is of a mechanical nature.

These results are a small part of the consideration given to this subject in the Western Electric Research Laboratories at New York. It may be of some interest to cite one or two experimental results for the same case as that assumed.

An experimental receiver of the ordinary type was constructed in which the eddy current effects were reduced to a minimum. The cores were soft iron in a form which is the equivalent of very fine laminations and for the diaphragm silicon steel was chosen on account of its high specific resistance. The case was made of Portland cement, this being chosen because we wished to avoid eddy currents in the case and to use a material with about the same coefficient of expansion as iron so as to keep the airgap constant with temperature.

In addition to the driving winding a 100-turn coil was put on close to the pole tip which could be short-circuited at will to represent an eddy current circuit. Measurements on this circuit enabled us to predict its effect on the impedance of the driving circuit. In accordance with the foregoing formulas the predictions could be checked by measurement. To cite simply one piece of data, with the 100-turn coil open, 2 β was about 4 deg., with it closed, 25 deg. The corresponding computed value was 23.5 deg. A second model had the artificial eddy circuit wound as a twin winding, in parallel with the driving circuit. With this arrangement for eddy currents the lag angle 2 β went from a very small angle to 130 deg., and the motional impedance was diminished from 31 ohms to 4 ohms.

A. G. Webster: This is what I call practical engineering. I should like to point out, as a matter of history, that the first problem of this sort solved was solved by James Clark Maxwell in his famous paper in 1865. Of course there are here three lines of equations instead of two. You know how Maxwell understood the impedance, as we call it now, because of the in-

vention of the word of Oliver Heaviside—that the presence of the secondary increases the resistance of the primary and decreases the inductance. We all know that now, but we did not know it then. Of course, then came Lord Rayleigh, who described the reactions of any mechanical system.

Harold S. Osborne: Engineers who are dealing with power transmission rather than with telephone work may feel more at home with the motional impedance diagram of the telephone receiver if they can consider that it is not an entire stranger but the first cousin of an old friend. I refer to the circle diagram of the induction motor in which, as in the telephone receiver, the secondary moves. In the circle diagram of the induction motor, as indicated in Fig. 2, the secondary current corresponding to a given load is represented by a chord of the circle $O\,I$. The secondary current is a measure of the reaction of the moving secondary on the magnetic flux of the primary winding. Similarly, in the motional impe-

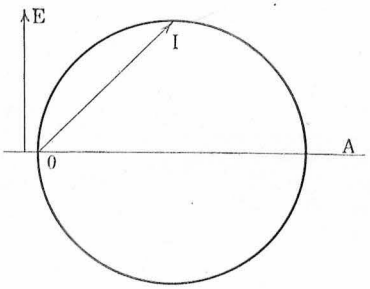


FIG. 2.

dance diagram of the telephone receiver, the reaction of the moving diaphragm on the fixed winding is represented by a chord of the circle $O\,V$, (Fig. 3).

There is a further close relationship between these two diagrams. The variable element seems to be different in the two cases because in the case of the induction motor we are considering variations of load, and in the case of the telephone receiver variations of frequency. However, in the induction motor variations in load mean variations in frequency of the secondary current, and one starts with zero frequency at point O, and goes half way around the circle to infinite frequency at point A. The other half circle corresponds to negative frequencies. In the case of the telephone receiver the law of variation in frequency in passing around the circle is, of course, different. In this case, starting with zero frequency at point O, one passes around the circle and at infinite frequency completes the circuit, arriving again at point O.

The difference in the use of the circle diagram for the induction motor and for the telephone receiver illustrates one difference between the problems of the power engineer and of the telephone engineer to which I should like to call attention. In the case of a power system, one is interested in studying the system under conditions of constant impressed e. m. f. and varying loads of a given frequency. In the case of the telephone system the load is, in general, constant but the frequency is varying.

The importance of a very wide range of frequencies in telephone work is, I think, an old story even to engineers who are not engaged in telephone work. Over thirty years ago Oliver Heaviside pointed out the effect of variation in efficiency of the telephone receiver with frequency, and the effect of that on the telephone quality. In those days people were still marveling

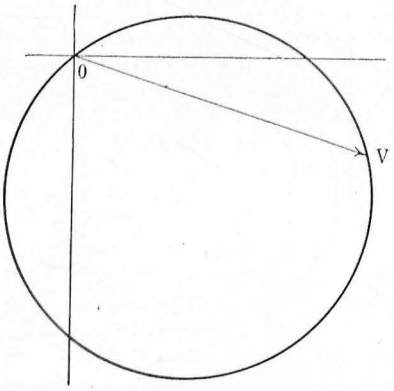


FIG. 3.

over the fact that this wonderful little instrument could reproduce speech, and that they were astonished at what seemed to them, perfection of articulation, and by the fact that one could even recognize the voice of different persons. However, Mr. Heaviside stated that to the critical observer the telephone quality was very far from perfect. As he expressed it, "the disk does not do it, for want of deadbeatness." The fact that telephony is practicable, he claimed, is not so much a triumph of the electrical art, as it is a triumph of the human brain, which has been trained for years, and, in fact, for centuries, in interpreting the very much distorted sounds that come to it.

I do not believe that there is a general appreciation of the very large amount of distortion of speech which takes place in an ordinary room. Prof. Webster has told us that the reflec-

tion from the earth is 95 per cent. From a wooden floor or walls of a building it must be very great. The reflected waves cause tremendously large variations in the magnitude of the different components of the speech sounds, and large differences in different parts of the room. In addition, there is the effect of room noises. Beyond that, there are personal factors which perhaps cannot be called merely physical matters, such as slovenliness of speech on the part of the talker, and defective and wandering attention on the part of the listener.

Now, although large advances have been made since Heaviside's day, the telephone receiver still is very far from a perfect reproducer of the energy supplied to it. However, when one considers the distortions to which ordinary speech is subject, and the fact that our ears through training are capable of understanding this distorted speech very well, it is not so surprising that we should be able to detect the distorted speech of the telephone circuit. It is probable that the difference in quality of conversation between listening in a room like this, and listening an infinite distance from everything, as Prof. Webster puts it, is much greater than the difference between listening in the room and listening over a telephone circuit.

The instruments and methods which Prof. Webster has shown to us are certainly of the very greatest interest to any one who has to deal with acoustic problems. However, electrical engineers, from the prejudice of their training, very much prefer to read their results on electric instruments when it is possible, rather than to observe them through a microscope as mechanical displacements.

Mr. Jones has spoken of the fact that, in many cases, we are very much interested in measuring sound with an instrument which is not highly selective, but which, on the contrary, responds so as to give as nearly as possible a faithful reproduction of a complicated wave shape, that is, an equal response to the different harmonic components of the wave. A good solution of this problem has been discussed in two papers which were printed in the *Physical Review* in July, 1917, which I would like to call to your attention. These are the "Thermophone as a Precision Source of Sound," by H. D. Arnold and I. B. Crandall, and "A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity," by E. C. Wente. By means of the instruments described in these papers it is possible to set up a system for transforming acoustic into electric waves and vice versa with an efficiency of conversion which can be made sensibly uniform throughout the range which is important in telephonic work. Of course, these instruments give very small responses, but in these days of vacuum tube amplifiers that is not a difficulty.

Mr. Taylor has spoken of the possibility of using Prof. Webster's instruments to study the characteristics of interfering currents in telephone circuits. However, for such complicated

wave shapes as those or for the study of the characteristics of telephone speech, instruments giving a uniform response, such as are described in the papers just mentioned are very much more valuable than instruments which are sharply tuned to particular frequencies.

A. G. Webster: I was very much interested in these papers when I heard them read. I went to New York with some qualms as to whether I had been anticipated. When I saw the amplifying tube I said, "That let's me out." Who knows whether the amplification of that tube is the same for all these frequencies. I said to Major Whitehead last year in his laboratory—"I have seen this wonderful description of the amplifier. Does it do it?" I will not tell you what he said, but those of you who have heard of experiments of that sort, will, I am sure, say that the electrical engineer is mistaken. We know that this is an exact thing, no hysteresis or eddy current. This is a perfection of simplicity, and therefore I recommend it. As to its being selective, it is selective. You can tune it to any one of these sounds and make a photograph and analyze it.

I believe I can give more satisfactory answers to all of these telephone engineer's queries than can be got by the instruments he gets up himself. They are handy, no doubt, and all that. I remember Lord Kelvin seeing one of my instruments several years ago, and he said "It was important that sound could be measured by electrical reading apparatus." I do not do it that way.

A. Press (communicated after adjournment): "May I draw the attention of the authors to a work of mine which antedates that of M. Marius Latour on "Hysteresis and Eddy Current Losses in Iron Plate." This paper appeared in *The Electrician* of London for July 23, 1915. It not only gave a solution of the plate problem but it also indicated a general method for solving problems in which what amounts to a difference of phase between H and B occurs. Since then a simpler method has been developed for dealing with all the harmonics set up by iron in any electrical circuit, the manuscript of which is now in press. Distortions and resonances due to hysteretic harmonic components can be very effectively handled by the methods indicated.

A. E. Kennelly: In reference to the set of equations which Dr. Jones has so clearly explained, it is interesting to observe how his algebraical and our graphical presentations of the behavior of the telephone receiver converge towards similar conclusions.

In response to Mr. Shea's question, the angle β is the angle between the vector damped impedance locus and the reactance axis of coordinates. Strictly speaking, this angle β is a function of the impressed frequency, and increases with increasing frequency. Nevertheless, it usually varies but little within the

range of frequency included between the quadrantal points of the motional impedance circle. Such variations as occur outside of those limits have relatively small disturbing influence.

In Fig. 1 of the Kennelly-Affel paper* (Bibliography 17) appears the locus of the damped impedance of the particular telephone receiver which is analysed in this paper presented today. In its Fig. 4 is the motional impedance circle. The depression angle 2β of the circle's diameter (see also Figs. 10 and 27 of todays paper) is approximately 50°.6. In Fig. 1, the angle β which the locus ABD, between B and D, makes with the reactance axis is very nearly 25°.3. The fact that this angle β as measured on the diagram of the original paper is very nearly half the angle of diametric depression of the motional impedance circle was only discovered after the paper here presented was written, and serves as a check upon the provisional theory. A complete theory, however, would call for a recognition in the change of β with impressed frequency.

We are all indebted to Dr. Webster for his exhibition here of this ingenious acoustic apparatus. The fact that he has been able to reduce the damping coefficient to so low a value as has been mentioned is a very valuable achievement in itself.