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THE FREQUENCY-SENSITIVITY OF NORMAL EARS.

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SYNOPSIS

Minimum Audible Pressure Variation for Tones of 60 to 4,000 Cycles.—The rather discordant results obtained by other investigators are briefly reviewed and are summarized in Fig. 1. In the present research an attempt was made to get results with a definite dynamical significance. A special air-damped telephone receiver held tightly to the ear, was excited by an alternating current of variable frequency from a vacuum tube oscillator provided with special low pass filters to eliminate upper harmonics, and the current strength was changed logarithmically by means of a special attenuator until the threshold was reached. The observations were made in a special *sound proof room* whose construction is described. The probable error is about 25 per cent. To reduce the results to absolute units, the system was calibrated in two ways, both involving the substitution of a condenser transmitter for the ear, the source of sound being a telephone receiver in one case and in the other a small thermal receiver inserted in the ear meatus or in a similar cavity in front of the condenser transmitter. *Mechanical analogues of the vibrating systems involved* in these measurements are described in an Appendix to help make the dynamics clear. While the unknown mechanical constants of the inner ear introduce some uncertainty, the agreement of the two calibrations indicates that the error is not large. *Frequency-sensitivity curves* were obtained for approximately *100 normal and 20 abnormal ears.* So-called normal ears were found to vary widely in relative frequency sensitivity and in absolute sensitivity, and some audiograms show interesting individual peculiarities. But on the average, the minimum audible pressure variation increases regularly from about 0.15 dyne/cm.^{2} at 60 cycles to 0.001 dyne/cm.^{2} at 1,000 cycles and is then approximately constant up to at least 4,000 cycles.

Variation of Sensitivity with Deafness.—People who require throughout the speech range (600 to 4,000 cycles) about 0.1 dyne/cm.^{2} are called slightly deaf; those requiring 1 dyne/cm.^{2} can still follow ordinary conversation; those requiring 10 dynes/cm.^{2} need ear trumpets or other amplifying devices, and those requiring 1,000 dynes/cm.^{2} are totally deaf.

Attenuator for Varying the Current from an Oscillating Tube through Wide Ranges was constructed. It consists essentially of an artificial transmission line with resistance sections of series and shunt arms, so designed as to eliminate interfering effects between the various elements. The range of variation obtained is three million fold.

A LARGE amount of work has been done during the last fifty years in an endeavor to determine in absolute terms the minimum amount of sound that the human ear can perceive. The results obtained by different investigators have varied throughout a very wide range. Two causes contributed to this: namely, that adequate apparatus was not available, and it was not appreciated that so-called normal ears vary so widely in their ability to hear.

It is important for the proper engineering of the telephone plant to know in absolute terms the sensitiveness of the ears of the average telephone user. For this reason this investigation was undertaken.

In 1870 Toepler and Boltzmann[1] made a determination of earsensitivity. The amplitude of vibration of the air particles in an organ pipe was determined by light interference methods. From the distance to the source at which sound was just audible it was possible to determine the amplitude of vibration of the tone at the threshold of audibility. The results of their measurements together with those to be described below are given in Fig. 1.

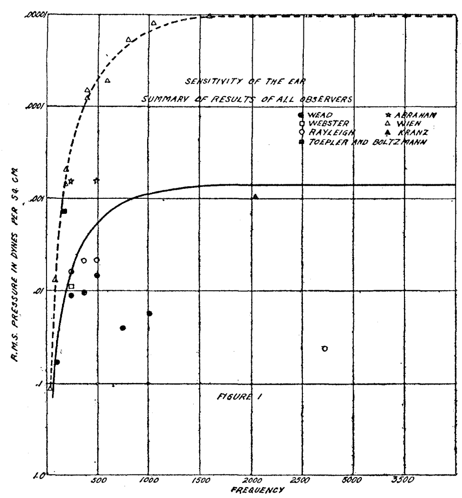

Fig. 1.

It will be noticed that the root mean square value of the pressure is plotted on logarithmic paper. This is necessary because of the wide range of pressures involved. The scale is arranged so that points high up on the plot indicate high ear sensitivity. The ordinates for all of the audiograms—sensitivity frequency curve for the ear—which are to be given later, are drawn on this same scale.

In 1877 Lord Rayleigh[2] used a whistle as a source of sound and calculated the energy emitted by it, from the pressure used in blowing it. He also used a tuning fork mounted on a resonator. From the difference in

[1] Ann. der Phys., Vol. 141, p. 321, 1870.

[2] Proceedings of Royal Society, Vol. 26, p. 248, 1877.

the decay constants of the fork suspended freely in the air and mounted on the resonant box, it was possible to calculate approximately the energy emitted by the box. He made a third measurement using a telephone receiver as a source. The deflection of the diaphragm for direct current was considered the same as for an alternating current when the period was far below the natural period. The former was measured microscopically and consequently when the volume of air enclosed in the ear is known it is possible to calculate approximately the change in pressure on the ear drum from the current flowing in the receiver.

In 1883 Wead[1] used a vibrating tuning fork in an open field as a source of sound. The amplitudes of vibration were made large enough to be directly measured. From the decay constants and the time elapsed before the tone disappeared the absolute values given on the sketch were determined.

In 1889 Wien[2] used a telephone receiver as a source of sound, making measurements of the amplitude of vibration for loud sounds. By assuming that the amplitude increases proportionally with the current it is possible to calculate the amplitude of vibration of the diaphragm at the threshold of audibility. He observed results through a range of frequencies from 50 to 16,000 cycles. The dotted curve in Fig. 1 shows his results.

In 1904 Webster[3] used for his source a so-called "Phone," an instrument so constructed that the emission of sound energy can be calculated. He obtained the value of the ear at 250 cycles of 9.0×10^{-3} dynes per square centimeter.

In 1905 Abraham[4] used as a source of sound a telephone receiver attached to a brass cylinder, the diaphragm forming its base and an earpiece its top. The change in pressure in the cylinder for a direct current in the receiver was determined by a sensitive manometer. He obtained approximately the same sensitivity for the two frequencies 250 and 500 cycles. These frequencies were well below the natural period so that the same proportionality factor was used for obtaining the pressure change as was obtained by the direct current measurement.

In 1921 Kranz[5] used a thermal receiver as a source of sound. From the theory of the thermal receiver and the volume of air enclosed in the ear he calculated the ear sensitivity at 2,048 cycles per second to be 9.6×10^{-4} dynes per square centimeter.

[1] American Journal of Science, 131, Vol. 26, p. 177, 1883.
[2] Ann. der Phys., Vol. 36, p. 834, 1889.
[3] Festschr., F. L. Boltzmann, Leipsig, 1904, p. 1866.
[4] Comptes Rendus, Vol. 144, p. 1099, 1907.
[5] Phys. Rev., (2) XVII, p. 384, 1921.

The results of these various observers are collected together and shown in Fig. 1. It is seen that there is a very wide range between the results of the different observers. For comparison the results which were obtained by us are shown by the heavy line.

The development of the vacuum tube amplifier and oscillator, condenser transmitter and thermal receiver has given us precision apparatus which has made it possible to make accurate measurements of ear sensitivity. In this investigation for most of the measurements the source of sound was an air-damped telephone receiver. This was held tightly against the ear and by means of a special vacuum tube oscillator alternating current at different frequencies supplied to it. The current was then reduced by means of a specially constructed current attenuator until the tone in the receiver was just audible.

All of the measurements were made in a room which was especially constructed to eliminate all outside noises. The top, the bottom, and the sides of this room were built of a number of alternate layers of loose felt and sheet iron, the final inside layer being felt covered with cloth. It is extremely important that all noise interference be eliminated in making measurements near the threshold of audibility. In a room having the ordinary noises from the street the threshold point may be shifted to ten times its value in a quiet place, and in very noisy places this may be increased to 1,000 times.

The construction of the attenuator played an important rôle in making it possible to determine accurately the threshold of audibility. It consists essentially of an artificial transmission line having resistance sections of series and shunt arms. It is so designed mechanically that the terminals of the receiver can be placed across this line and moved along it at will. This is accomplished by simply moving a single dial switch, the complete scale of which represents a variation in current of more than three million fold. The network is so designed that each step corresponds to a certain fractional decrease in potential across the receiver terminals. As the contacts are moved uniformly from the input end toward the output end of the network the intensity of sound coming from the receiver decreases logarithmically. Considerable difficulty was encountered in the construction of this attenuator owing to the high attenuations involved. It was only after considerable experimenting and adjusting that it was possible to eliminate interfering effects due to the capacity between the various elements and to the small resistance in the heavy lead wires. A schematic circuit drawing and a photograph of the complete attenuator is given in Fig. 2.

The air-damped telephone receiver was constructed so that the diaphragm was damped by a small film of air in a manner similar to that used in the capacity transmitter as described by Crandall and Wente.

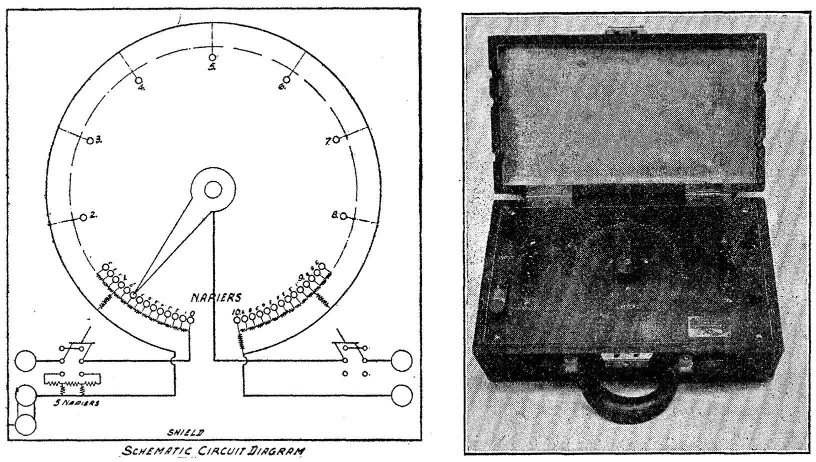

Fig. 2.

The vacuum tube oscillator was equipped with special low pass filters. These were designed so that all harmonics produced in the oscillator were reduced in amplitude more than one thousand times before they entered the attenuator. It is important that such precautions be taken especially at the low frequencies for it will be seen from the results which were obtained that a tone at 1,000 cycles per second requires only 1/60th as much pressure variation for audition as for a tone at 100 cycles per second. Two methods of calibrating this system were used, both depending upon the calibration of the condenser transmitter. The method of calibrating the latter has been described by Crandall[1] and Wente.[2] It consists essentially in determining the voltage generated with a measured pressure change in the diaphragm. The calibration obtained by means of an enclosed thermal unit was checked at low frequencies by an alternating pressure produced by a positively driven piston and at 600 and 1,000 cycles it was further checked by calculation[3] from the motional impedance of a permanent magnet receiver which was clamped tightly over the condenser transmitter.

The first method of calibration was made possible by the construction of a high-quality telephone system described in a paper given at the Washington meeting of the Physical Society, April 23, 1920. A schematic dia-

[1] Crandall, Phys. Rev.. (2) XI, p. 449 (1918).

[2] Wente, Phys. Rev., (2) X, p. 39. 1917.

[3] R. L. Wegel, Journal A. I. E. E., Oct., 1921.

gram of this circuit is given in Fig. 3. By adjusting the potentiometer it

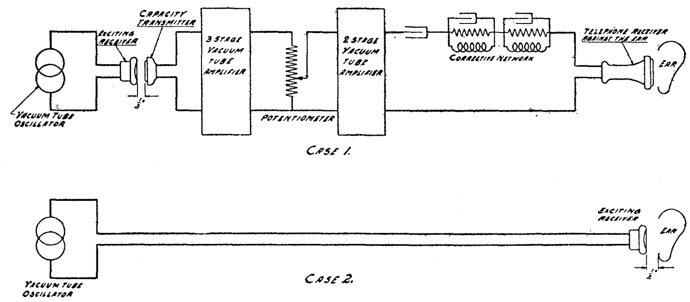

Fig. 3.

was possible to make the tone coming from the system receiver B (Case I.) sound exactly as loud as that produced when the ear was held in the same position as the condenser transmitter (Case II.). This reading of the attenuator was found for all frequencies from 100 to 2,000 cycles. Since the sound energy striking the condenser transmitter was known in terms of the voltage generated by it, the energy going from the receiver of the system into the ear of the observer could then be calculated from the potential difference at the terminals of the condenser transmitter and the reading of the attenuator.

To make a measurement a potential difference of known magnitude and frequency was applied at the terminals of the condenser transmitter and sufficient attenuation was introduced into the system to make the sound from the receiver inaudible. The attenuation was then gradually removed until the sound just became audible. From the amount of attenuation for this condition and the voltage impressed upon the terminals of the condenser transmitter the pressure variation in the ear was calculated. Four or five readings were taken in this way which gave an average value having a probable error of 20 or 30 per cent. in the determination of the pressure variation. This method was used for making tests with 11 different observers—seven men and four women, through a range of frequencies from 130 to 2,000 cycles per second. The average of the results is shown by curve 1 in Fig. 4.

In the second method of calibration a thermal receiver unit small enough to be inserted in the external auditory meatus of the ear and completely close it, was used. It consisted of a series of short Wollaston wires enclosed in a small brass capsule with small holes communicating with the outside air. A small chamber was made in front of the calibrated condenser transmitter diaphragm equal in volume to that of the external ear. The thermal receiver was inserted in a hole in this chamber in such a way as to make it airtight. A sketch showing the details of the coupling between the condenser transmitter and thermal receiver is shown at the bottom of Fig. 5.

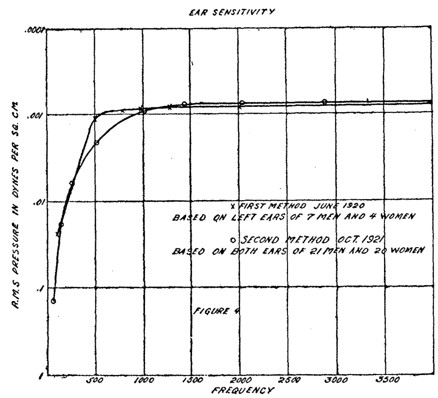

Fig. 4.

The relation between the voltage impressed upon the thermal receiver and the pressure exerted by it on the condenser transmitter diaphragm was then determined experimentally. The apparatus used in this work is illustrated in Fig. 5.

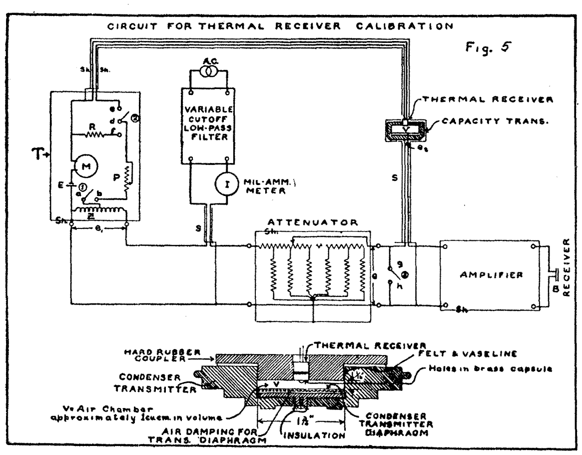

Fig. 5.

By means of this arrangement a known electromotive force is introduced into the condenser transmitter circuit which is equal to that generated by the condenser transmitter when actuated by the thermal receiver. This equality is established by listening at the receiver B. By means of the switches the tone from this receiver is first produced by the condenser transmitter and then by current through the attenuator. When the latter is adjusted so that the tone sounds equally loud from either source it is evident that the equality is established. In this way a calibration curve was made showing the pressure variation produced by the thermal receiver unit against the condenser transmitter at various frequencies when a unit e.m.f. is impressed upon the thermal receiver circuit contained in the box T.

The first thermal receiver unit which was used had a single aperture in the brass capsule of approximately .1 millimeter in diameter. The calibration curve for this receiver is shown as curve a in figure 6. An addi-

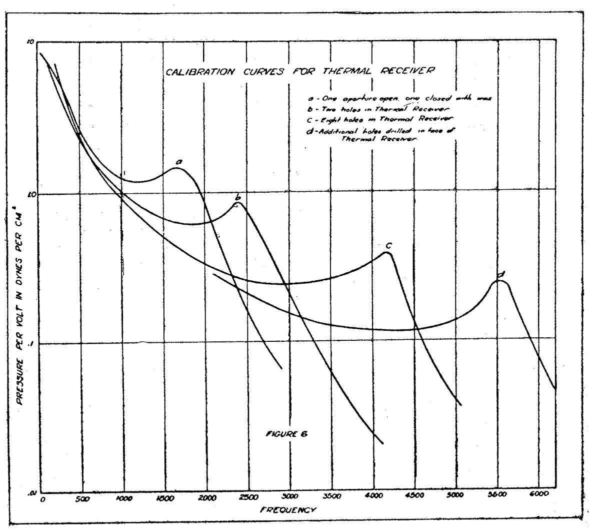

Fig. 6.

tional hole was drilled in the receiver and then it was recalibrated, the curve b showing the result. Similarly, by drilling more holes in the receiver the calibration curves c and d were obtained. The shifting of the resonant peak in this manner is explained by Rayleigh's formula which gives the resonant frequency of an enclosed sphere of air having a small opening. According to this formula

$$f = \frac{a}{2\pi} \sqrt{\frac{C.}{V}}$$

where f is the resonant frequency in cycles per second; a the velocity of sound in air; C the diameter of the connecting circular aperture and V the volume of the resonator. In this experiment the volume of the enclosed air was approximately 1 cubic centimeter. By applying the formula and using this figure and .1 centimeter for the circular aperture the resonant frequencies for A and B calculate to be 1,710 and 2,400 respectively, which agrees with the observed result. Curves c and d were finally used for calibrating the air-damped receiver system.

Using these two thermal receivers the minimum audible pressure was calculated from the minimum audible current when the thermal receiver was inserted in the ear. Simultaneous measurements were made with five people using first the air-damped receiver and then the thermal receiver. From a comparison of the results the latter system was calibrated. The probable observational error in this determination was found to be 8 per cent. in the range of frequencies from 500 to 3,000 cycles.

It is seen from the manner in which the measurements were made that the first method of calibration gives directly the pressure variation at the opening of the external ear provided only that the ear reflects the sound waves the same as does the condenser transmitter when placed in the same position. Also in the second method the pressure variation which is computed is that which would be exerted upon the ear drum provided that it had the same stiffness as the condenser transmitter diaphragm. Since the ear drum moves and its mechanical impedance at some frequencies may be comparable with that of the ear chamber the actual pressure variation against the ear drum may be somewhat less than that given in the curves.[1] As a matter of fact the two methods give approximately the same results as is indicated by the two curves 1 and 2 in Fig. 4. This agreement seems to indicate that the pressures which are given are not very greatly different from those which are actually exerted upon the ear drum. As indicated by these curves the average sensitivity for normal ears varies from .15 dyne at 60 cycles to .001 dyne at 1,000 cycles. Between 1,000 and 4,000 cycles per second the sensitivity is approximately constant and equal to .001 dyne per square centimeter.

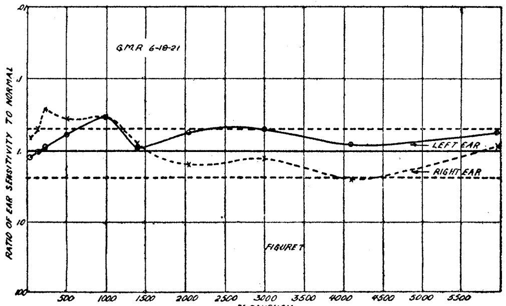

Fig. 7.

[1] For a discussion of the mechanical reactions involved see the Appendix.

Figure 7 shows a typical audiogram for a person of normal hearing. At any given frequency, the average sensitivity for all the observers of normal hearing as shown in Fig. 4, was used as the norm in plotting this and succeeding audiograms. Fig. 8 gives the audiograms of twenty women. A set of curves for twenty-one men were taken which was practically a duplicate of Fig. 8. The probable observational error is

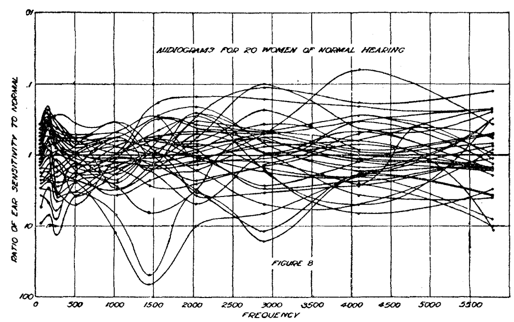

Fig. 8.

approximately 25 per cent. The probable deviation of any observed value from the average normal, including the observational error and the variation in the sensitivity of different normal ears, is approximately in the ratio of one to two.

It will be seen that an audiogram oscillates more or less about normal and that different ears vary greatly in this respect. Fig. 9 is a representative careful run made on a single ear and shows that a large number of small peaks actually occur. It might be noted that these vary more or less from day to day in a single ear. In averaging the audiograms of a large number of people these small peaks would cancel and consequently it was not necessary to make such careful runs on all the forty-one people who were tested.

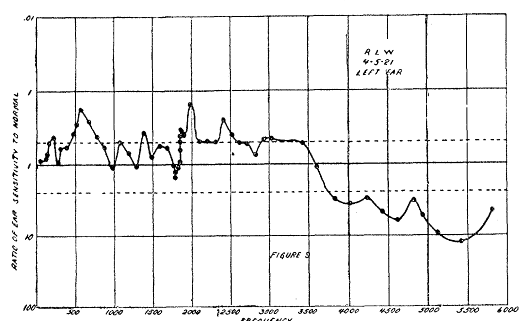

Fig. 9.

Figure 10 shows an audiogram of a person who was supposed to have

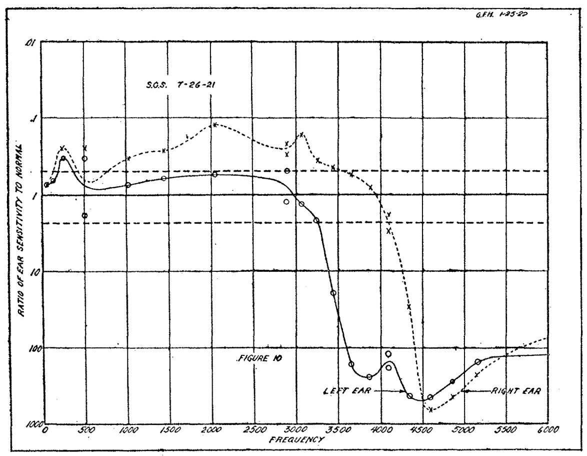

Fig. 10.

normal hearing but for some cause his ears acted like a filter cutting off at a frequency at about 3,000 cycles. Audiograms for people of various types of deafness show striking differences in their relative frequency sensitivities. It is expected to make a complete report of work along this line in the very near future. It is sufficient here to give from our general experience the amount of sound volume in the speech range that is required to make people of various degrees of deafness hear. Persons who have normal hearing require approximately 1/1000 dynes per square centimeter in order to hear sounds in this range. Persons who require a pressure variation of 1/10 dynes per square centimeter are called slightly deaf. Those who require one dyne are partially deaf but can usually follow ordinary conversation. Those who require 10 dynes belong to that class who use ear trumpets or deaf sets to amplify the speech waves. A pressure variation of approximately 1,000 dynes can be felt and produces a sensation of pain. For practical purposes it may be assumed that people who experience no auditory sensation at these pressures are totally deaf.

This shows that among people who can follow ordinary conversation there is a range in ear sensitivity of more than 1,000 and among people who are noticeably deaf there is another range of 1,000, making a total range of more than a million for people who can hear or be made to hear by means of amplifying devices.

In conclusion we desire to express our indebtedness to Messrs. F. W. McKown, F. H. Graham and C. E. Dean who have assisted in various phases of this work.

APPENDIX.

From a dynamical standpoint the phrase "sensitivity of the ear" as it is usually used is rather indefinite. When a figure is given in ergs per second, the rate of flow of energy through an area equal to that of the ear opening in an unobstructed wave, is meant. This has no simple relation theoretically, at any rate, to the net rate of flow of energy into the ear when the head is placed as an obstruction to the wave. The distortion of the sound field by the head varies greatly with frequency. Similarly, there is no simple relation between the energy flowing into the ear and that transmitted to and absorbed by the ear drum or by the cochlea. In the experiments recorded above, some attention was paid to the experimental set-up so as to make the figures given have a more definite dynamical significance. Sensitivity is given in terms of the alternating (root mean square) pressure to produce a minimum audible sensation. Just what is meant by pressure is best explained with reference to the schematic diagrams shown in Fig. 11.

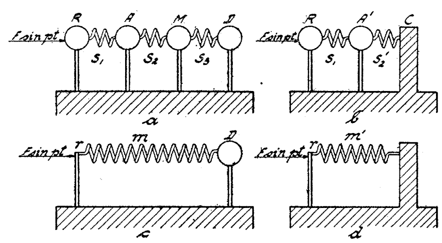

Fig. 11.

Diagram a represents schematically the vibratory system involved in the case of the measurements by means of reproduction ratio, simplified, of course, for the sake of easy demonstration. A series of four weights supported by springs and connected by springs is shown. If each of these elements be considered as being made up of properly distributed combinations of dynamical coefficients of mass, stiffness and friction (*i.e.*, so as to give a proper action and reaction between R and D), we may regard the element R as representing the telephone receiver diaphragm acted on by a force $F \sin pt$ of the electromagnet; A as air space between the receiver diaphragm and the opening to the ear; M as the external ear canal and D the ear drum with its attached apparatus. The second diagram, b, represents schematically the set-up for calibration, in this case, of the telephone receiver R with the capacity transmitter C. In this case A' represents the air space between the receiver and the capacity transmitter C which may be regarded as practically rigid. The calibration consists of measuring the pressure on C per unit of force

$(F/\sqrt{2})$ acting on the receiver diaphragm. If we assume that the sound fields between receiver and head and between receiver and capacity transmitter are identical, then the elements s_2 and A are identical with s_2' and A' respectively. The area of opening of the external ear canal is not equal to the area represented by the capacity transmitter diaphragm so s_2 and s_2' are not identical, but if it is agreed that allowance can be made for the difference by using pressure per square centimeter, the relation between s_2 and s_2' may be assumed to be known. The calibration then gives the force in dynes per square centimeter acting on M if M is held rigid. This corresponds to having the auditory canal stopped. Since, however, M, the air in the ear canal, is movable, the force on this area is different from that given by an amount depending on the vibratory characteristics of M and D and their relation to A. The curves of sensitivity may then be considered to be (within the error of measurement and of experimentally matching a and b) the pressure sensitivity of the entire auditory apparatus including the vibratory characteristics of the air space between the receiver and head, the ear canal and the drum.

The dynamical system involved in the measurement with the thermal receiver is less complex. Diagram c represents the system in this case. The mechanical impedence of the thermal receiver is practically of pure elasticity represented by the vertical spring r. This represents the elasticity of the active cushion of air around the thermal element which includes a volume of approximately .01 cc. (see paper by H. D. Arnold and I. B. Crandall in PHYSICAL REVIEW, July, 1917, on the thermal receiver), and assumes the measurements to be made well below the resonance of the air cavity as shown in Fig. 6. The volume enclosed in the ear is about 1 cc. so that the elasticity m representing this element is negligibly small. D represents the ear drum. Diagram d is the schematic representation of the calibrating system in which r is the thermal receiver, m', a cavity in which the receiver was inserted in front of the capacity transmitter C. m' was made equal in volume to the volume of the ear cavity m. Since the reaction in both systems c and d on r are negligibly small, because of the lack of stiffness of the spring (air chambers m and m'), this measurement gives the overall sensitivity of the ear including the vibratory characteristics of the drum and 1 cc. of air enclosed in the external auditory canal.

The close check between curves obtained by both methods (see Fig. 4) indicates that the difference between the two vibratory systems is very small within the range of frequencies measured.

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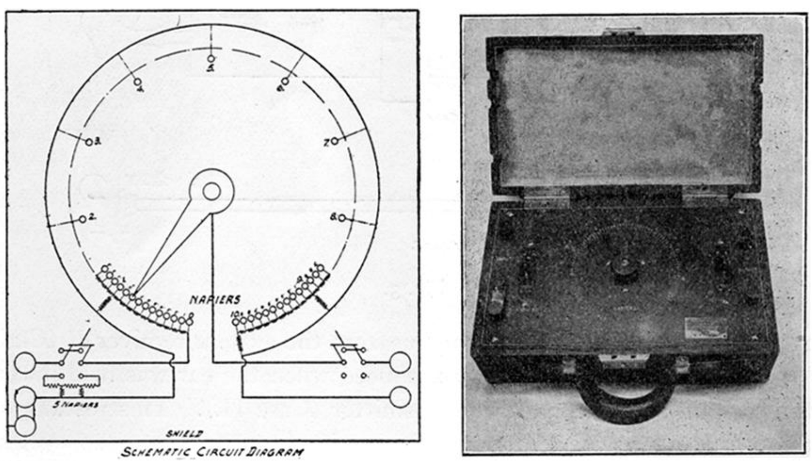

Fig. 2.