# The Physical Characteristics of Audition and Dynamical Analysis of the External Ear

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SYNOPSIS: This paper discusses some of the characteristics of the ear which have become important in the design and development of telephone apparatus and circuits. The field of audition, bounded by the curves of minimum and maximum loudness as functions of frequency, has been determined for a large number of ears, and the smaller included area most used in speech has been mapped. The nature of these fields in certain cases of abnormal hearing has also been determined and the conditions which must be observed in designing apparatus to satisfactorily relieve deafness are discussed.

The sensitivity of the ear is given in terms of the r. m. s. pressure measured by a calibrated condenser transmitter. It is printed out in the appendix that this pressure is not necessarily equal to that which, when applied to the ear drum, would just give rise to the sensation of sound. However, it is the nearest approach to the value of this pressure which can be determined at present, and as the dynamical properties of the ear become more fully known it is pointed out how the relation between the two pressures can be more accurately stated.—*Editor.*

1. *Introduction.* It has become important in the design and development of telephone apparatus and circuits to know quantitatively the various functional characteristics of the ear since the ear is an important dynamical unit in the long series of vibration transmitting apparatus constituting a telephone system. A complete analysis of this problem involves not only the properties of the physical circuit, but also the characteristics of the ear and voice and of the air passages between the mouth and transmitter and between the ear and receiver. It is the purpose of the present paper to discuss some of the characteristics of the ear and its outer air passages.

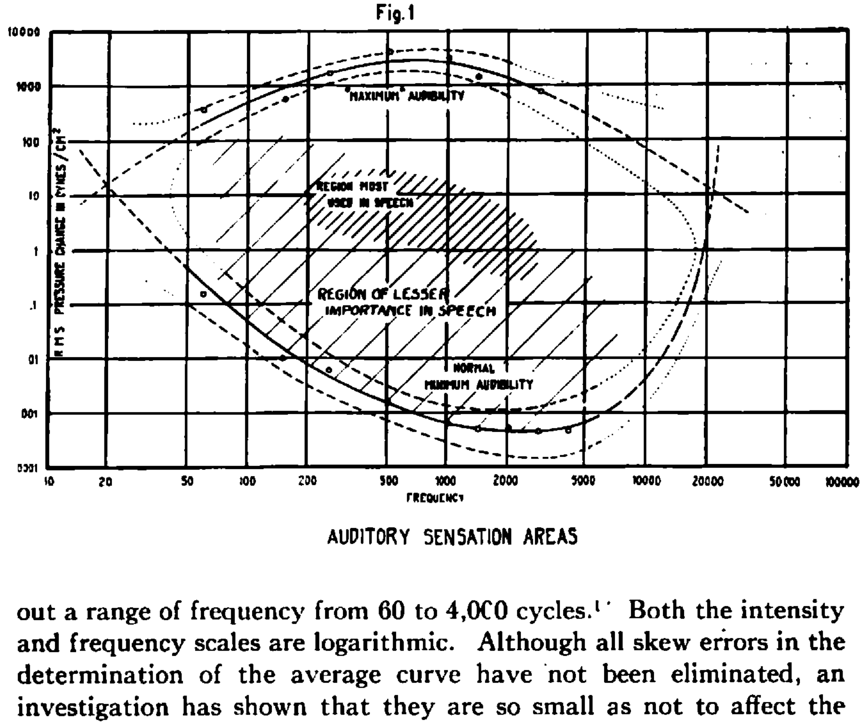
Much has been learned about the normal ear by the investigation of the characteristics of abnormal ears. This has incidentally had an application to otological diagnosis and the design and building of amplifying apparatus for the deaf.

This paper is a summary of the conclusions reached to date regarding the absolute sensitivity of normal and abnormal ears, the maximum sound to which the ear can accommodate itself, the much discussed points of "upper and lower frequency limits of audition," the "quality" of audition, a brief mention of the binaural sense and the principles of rigorous dynamical analysis of the ear as a mechanism. A brief description of the apparatus used is also given.

The function of the auditory sense is to detect sounds of various kinds and wave shapes varying over a range of pressure on the ear drum of from about .001 to 1,000 dynes per cm$^2$ and over a considerable part of this range to differentiate with certainty between complex sounds so nearly alike that no existing physical apparatus can separate them. The binaural feature adds a sense of orientation with respect to a source and uniform sensitivity for sounds approaching from different directions. The abnormal auditory sense may be regarded as lacking more or less in (a) range of sensation (frequency and intensity); (b) quality of sensation in various regions of the range; (c) the binaural sense. Apparatus and methods have been developed by means of which the outstanding features of these functions can be measured and to a limited extent compensated for.

2. *Minimum Audibility.* Fig. 1 shows a plot of the logarithmic average of minimum audible pressure on 72 normal ears taken through-

Fig. 1




AUDITORY SENSATION AREAS

out a range of frequency from 60 to 4,000 cycles.[1] Both the intensity and frequency scales are logarithmic. Although all skew errors in the determination of the average curve have not been eliminated, an investigation has shown that they are so small as not to affect the utility of the curve for the purpose of measuring deafness. Among the errors which obviously tend to raise this curve might be mentioned, noise in the observing room, abnormality of hearing, lack of attention, and low mentality of the observer. Care was taken to reduce these errors to a minimum without actually making separate

[1] This curve has already been published; The Frequency Sensitivity of Normal Ears, by H. Fletcher and R. L. Wegel, *Proceedings of the National Academy of Sciences*, January, 1922, and *Physical Review*, June, 1922.

quantitative measurements of each of them on a rigorous statistical basis.

The statistical deviation from the mean varies irregularly with frequency; very likely this is due mostly to the external anatomical variations in ears which cause deviations in the dynamical constants of the transmission system from sound source to the ear drum. The dotted lines following the curve of minimum audibility represent approximately the "standard deviation."

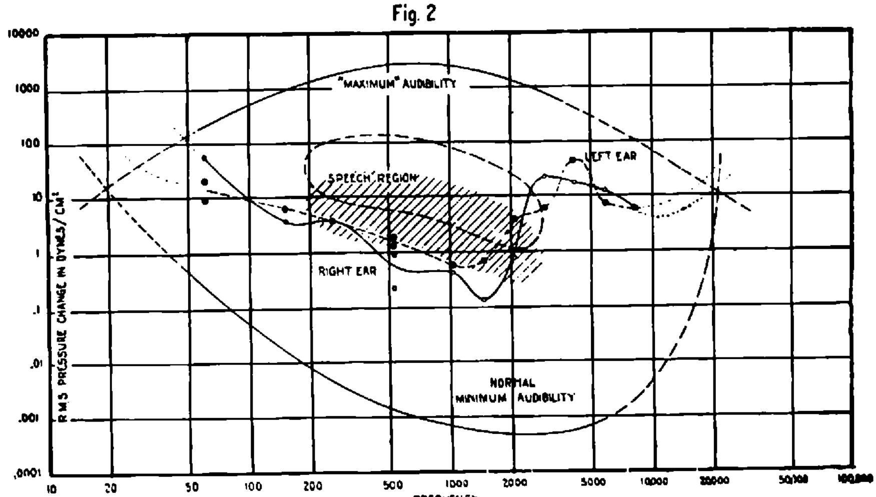
3. *Maximum Audibility.* The curve marked "Maximum audibility" represents the logarithmic average pressure on 48 normal ears required to produce the sensation of feeling. This represents the threshold of feeling in the same way that the minimum audibility curve represents the threshold of audition. A sound much louder than this is painful. The measurements were taken through a range of from 60 to 3,000 cycles. The standard deviation lines are also given from which it will be seen that this curve is quite as definite as that of minimum audibility. While this point of feeling probably has no relation to the auditory sense it does serve as a practical limit to the range of auditory sensation. A few observations indicate that people with abnormal ears have a point of feeling sound which is not greatly different from that of normal ears, but this, of course, depends on the type of abnormality. The intensity for feeling is about equal to that required to excite the tactile nerves in the finger tips.

4. *Lower and Upper Frequency Limits of Hearing.* The curves of minimum and maximum audibility in Fig. 1 will be seen to have been extrapolated to the points of intersection at high and low frequencies. The feeling sensation in the middle range of frequency is first a tickling sensation and then becomes acutely painful as the loudness is increased.. As the frequency is decreased the sensation of feeling becomes milder until frequencies around 60 cycles it is sensible as a flutter, but still quite different from the sense of audition. As the frequency is still further decreased to a point where the hearing and feeling lines appear to intersect, it is difficult to distinguish between the sense of hearing and that of feeling. The low point of intersection of the two normal curves of minimum audibility and feeling sense may, therefore, be taken arbitrarily as the lower tone limit of audibility. For frequencies lower than this it is easier to feel than to hear the air vibration. The point of intersection cannot be determined by direct observation due to the difficulty in distinguishing between the two sensations. A similar intersection of the two curves occurs at some very high frequency. Sound waves of frequencies below the lower intersection and above the upper intersection are more easily sensed

by feeling. Sound waves between these limits are more easily sensed by audition.[2]

This suggests a rational way of defining and determining the two frequency limits of audibility. Measurements of these limits which have been made in the past are questionable because the intensity factor has been neglected. At the lower limit of audibility the excursions of the diaphragm and ossicles of the middle ear are probably so large that the nerves feeding these movable parts are stimulated. This observation at low frequencies as indicated in this work lends color to the hypothesis of otologists that abnormalities in the hearing

Fig. 2




SENSATION AREAS (CHK)

of low frequencies are due to pathological conditions in the middle ear. This point is probably related to the tests on flexibility of the ear drum or ossicular chain due to the application of air pressure as observed by otologists in examination. Loss of sensitivity at low frequencies is considered an indication of obstructive deafness if there is no loss at high frequencies.

5. *Sensation Area.* From the combined standpoint of utility and logic the logarithmic relation between stimulus (pressure variation) and sensation can be assumed. The elliptical area between the two curves may then be taken to represent an area of sensation which is

[2] The extrapolation upward of the curve of minimum audibility is consistent with some recent observations of Mr. C. E. Lane at the University of Iowa, *Physical Review*, May, 1922.

characteristic of the normal ear. Any point within this area represents a definite auditory sensation in frequency and intensity. The area of sensation is analogous to the field of vision of the eye. The part of this area which is most utilized in the interpretation of speech is represented approximately by the shaded area in Figs. 1 and 2 and corresponds in a way to the center of the field of vision. A normal listener tries, by keeping at a certain distance from a speaker, to bring this part of his sensation area into play in the same way that when examining an object he directs his eyes so that it falls in the center of the field of vision.

An abnormal ear may be regarded as having an area of sensation which is smaller than the normal area but included within it. Fig. 2 is a plot of the minimum audibility of the right and left ears for a man (CHK) having a "catarrhal" deafness. The areas between these curves of minimum audibility and the curve of feeling are his areas of sensation. It will be seen that CHK retains about 50 or 60 per cent of the normal amount of sensation. He hears and interprets conversation with some difficulty.

Since the CHK curves pass through the speech region, part of it is entirely inaudible and the remainder is near minimum audibility for him. In order to make him hear well, the speech area must be raised to a higher level of intensity or loudness as indicated by the dotted curve.

In general it takes a loss of about 20 per cent of the sensation area to become noticeable and much more is disagreeable. A loss of 50 per cent requires the use of deaf apparatus. A loss of 75 per cent can be aided considerably by the use of high powered amplifying apparatus.

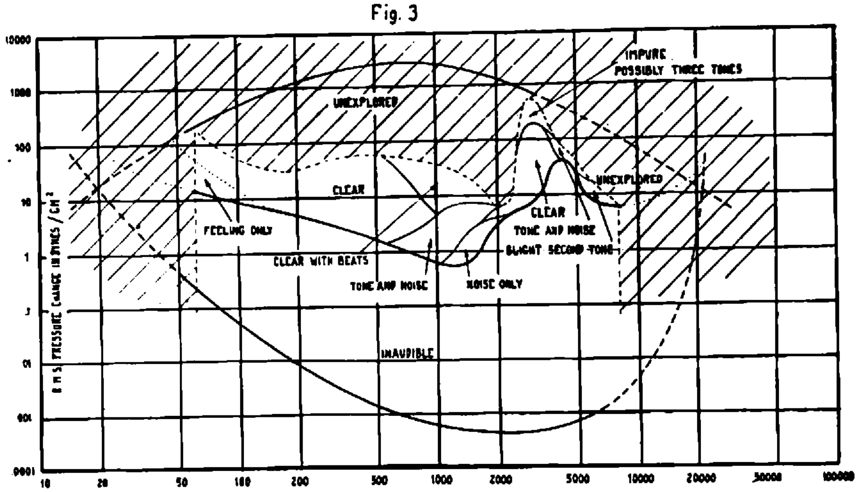
6. *Importance of Various Intensities in Speech.* It is interesting to speculate on how CHK interprets speech. It has been shown [8] that the intensity of speech may be varied over perhaps 70–80 per cent of the range of sensation without serious loss of intelligibility to the normal ear. As the sound intensity is decreased, the intelligibility drops very suddenly to zero at minimum audibility. A similar drop is to be expected at an intensity so loud as to be painful. It is evident, therefore, that the range in which speech is intelligible for CHK is very considerably limited as compared to normal. It is possible to design a deaf set which raises the intensity of the principal speech region to any desired place within the abnormal sensation area and so in a measure, compensate for this narrowed range. The region in Fig. 1 "Region of Lesser Importance in Speech," corre-

[8] H. Fletcher, *Journal of the Franklin Institute*, June, 1922.

sponds to stimuli in conversation of lesser energy content, such as the minor shadings and fainter consonant sounds. While it is physically possible to produce an amplification of speech so that this region is raised into the diminished area it is impracticable to do so because of the pain which would be caused by the louder components. A diminution in sensation area can, therefore, be only partially compensated for. In case the area is extremely narrow a deaf set furnishing optimum volume can only serve as an aid to lip reading.

7. *Quality of Hearing.* The sensation of a normal ear at any point in the auditory sense range (Fig. 1) may be described by a number of different adjectives, such for example as "clear," "musical," "even,"

Fig. 3




QUALITY AREAS-LEFT EAR (C.H.K)

"sustained," "smooth," "pure," etc. Such a description may, in fact, be taken as a reasonable indication that the quality of sensation at the point in question is normal. Abnormal ears sometimes experience a subjective degeneration of quality of pure stimuli which they describe as "rough," "harsh," "sharp," "buzzing," "vibrating," "hissing," etc. This subjective degeneration is independent of any tinnitus or head noises which the patient may have. Fig. 3 shows various regions of the sensation area which are degenerated in the case of CHK, left ear. The shaded area was not explored. The boundaries of the degenerated regions are usually more sharply marked than the outer boundaries of the sensation area. The sensations in these areas are so radically different from the sensation of a pure tone that it is with difficulty that the patient is convinced that the stimulation is the same pure tone to which he has been listening at the other intensities. The subject of these tests is a violinist and capable of better descriptions and finer distinctions than average.

Since all speech sounds may be considered as stimuli composed of various frequency components of certain intensities, the sensation caused by such a sound may be represented on this plot by points, or by a line provided the sound has a band spectrum. If the points or line, falls within the sensation area the sound is audible. It is easy to see that if the points or the part of the line which represent those frequency components most essential to interpretation of the sound, fall within any of these abnormal areas, the sound is very likely to be misinterpreted. This adds a further source of loss in intelligibility to that already observed due to a narrowing of the sensation range. When an amplifying deaf set is designed, due care should be taken to raise the principle speech region in such a way as to cause a minimum overlapping with the abnormal areas.

Many practically normal ears have very small abnormal areas. They have always been found near minimum audibility and if this is always true would, therefore, have little influence on the hearing of the individual. They seem to be associated with "catarrhal" conditions although this cannot be stated positively.

8. *Binaural Sense.* The normal individual has learned to interpret the differential sensations of the two ears to advantage. It helps him to locate the direction from which sounds come, to have a sort of sense of orientation with respect to sounds approaching from different directions, and whether for physical or for purely psychological reasons to assist in focusing of the attention on one sound of a large number. Two ears also assist the individual in perceiving equally well sounds coming from different directions.

When one ear becomes less sensitive, even though the loss is small, the use of the binaural sense disappears and after a time is not missed, the subject depending upon other means of locating sounds. For the binaural sense to be most effectively utilized it is necessary that the ears be very nearly alike. When a binaural deaf set is made and fitted to a person with compensating sensitivity for the two ears so that both hear the sounds equally loud, the sensation is usually so novel, that if the patient is actually able to experience a binaural sensation he is very much pleased. Usually, however, he has not used his binaural sense for so long a time that it takes a considerable amount of practice before he is able to have binaural experiences. It may be noted in this connection that the same experience is encountered in fitting the eyes with glasses. It is found that people with two eyes which are slightly different do not see stereoscopically but if glasses are made so as to compensate and make the eyes nearly alike, it usually takes a certain amount of practice before the sense of perspective can be brought back.

## APPENDIX

9. *Experimental Methods.* In order to discuss the principles of ear sensitivity measurement on a rigorous dynamical basis, it will perhaps, be clearer to describe briefly the experimental method used in producing known sound pressure in the ear canal at the various frequencies and intensities.[4]

As a source of sound, a small thermal receiver unit was used. This consisted of about twenty very small loops of Wollaston wire contained in a brass case small enough to be inserted in the external ear canal and entirely stop it up. In the average ear a volume of about 1 cm.$^3$ of air is included between it and the drum membrane. A direct heating current is passed through the receiver and an alternating current of the desired frequency and intensity is superimposed to modulate its temperature. This modulation in temperature causes alternate expansion and contraction of a very thin film of air covering its surface and so produces alternations in pressure in the ear canal of the frequency of the impressed alternating current. The intensity is proportional to this alternating current if it is maintained small compared with the direct current. This arrangement permits of producing alternating or sound pressure on the ear drum with a comparatively simple dynamical relation between the source of sound and the ear drum. The thermal receiver is also dynamically one of the simplest sources of sound known.

The sound or alternating pressure was determined by calibration. This was done by inserting the thermal receiver in an air cavity of 1 cm.$^3$ volume in front of a condenser transmitter diaphragm by which the alternating pressure developed by a given current in the receiver could be measured.[5] By measurement of the current for minimum audibility or "maximum audibility" or for any other intensity the pressure in the ear canal is determined.

10. *Dynamical Principles of Ear Measurements.* From a dynamical standpoint the phrase "sensitivity of the ear" as it is usually used is

[4] For further details, see "The Frequency Sensitivity of Normal Ears," H. Fletcher and R. L. Wegel, *Physical Review*, June, 1922.

[5] For the method of calibration of the condenser transmitter, see article by H. D. Arnold and I. B. Crandall, *Physical Review*, July, 1917.

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 commonly 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, 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. The term "pressure" has so far been used in a rather loose sense. Just why this is so will be seen from the following argument.

The simplest method of describing the constants of a mechanical system is in terms of the components of its mechanical impedance and their relative dispositions in the same way that an electrical circuit is described by giving its resistance, inductance and capacity and the way in which they are connected. In a linear system having a single degree of freedom, the impedance may in general be written in the form

$$Z = r + wjm + s/jw.$$

The symbols are as follows:

$j = \sqrt{-1}$,

$w = 2\pi$ times the frequency,

$r$ = frictional resistance to motion, with respect to a stationary body and involves dissipation of energy at a rate of $\dot{x}^2 r$ where $\dot{x}$ is the root mean square value of the relative velocity. The velocity $\dot{x}$ will be assumed simply sinusoidal in what follows,

$m$ = mass or inertia constant involving an average storage kinetic energy of $\dot{x}^2 m$ through one cycle,

$s$ = stiffness constant involving an average storage of potential energy through one cycle of $\dot{x}^2 s/w^2$.

If the r. m. s. alternating force acting is $F$, the motion at any frequency is given by

$$\dot{x} = F/Z.$$

In analyzing a system in which the constants may be considered as "lumped," that is in which, for the purpose of practical solution, a finite number of degrees of freedom may be assumed, the method is to find the most useful way of "lumping" these constants. The motions are then represented by a series of equations, one for each degree of freedom, between the forces acting and the impedances and velocities. The determinant of the coefficients of these equations is the Lagrange determinant of the system. The only caution to be observed in lumping the constants is that the reciprocal relation, which is a property of any linear system holds also for the physical system which the assumed Lagrange determinant is supposed to represent.

The method may be illustrated by the following application to the sensitivity measurements described above.

The dynamical system used in calibration with the condenser transmitter consists of three parts:

(a) The very thin pulsating air film over the thermal receiver filaments. The expansion of air around the wires is represented by the "diffusion" equation, the solution of which in such a case of cylindrical symmetry is given as a Bessel's function of the distance from the wire.[6] This wave is so quickly damped in travelling away from the wire as to be negligible beyond the first zero point of the Bessel's function. The vibrating system of this receiver may then be considered as a cushion of air next to the wire of a thickness a little less than the first half wave length of the heat wave. The thickness of this cushion is an inverse function of the frequency.

(b) The air chamber between the thermal receiver and condenser transmitter diaphragm having a volume of 1 cm.[3] and enclosed by practically unyielding walls with no openings.

(c) The condenser transmitter diaphragm, being stretched very tightly and air damped. It may also be regarded as unyielding, or as having an impedance very high compared to that of the connecting air chamber.

If for simplicity the mass reaction and internal losses in the air chamber may be neglected, it may be seen that the moving system of the receiver may be regarded as a weightless and frictionless "diaphragm" surrounding the wires at a distance equal to the effective thickness of the active air film and may be shown to have an intrinsic stiffness reactance of:

$$Z_1 = \frac{s_1}{jw} = \frac{\gamma p_0 a_1^2}{jwv_1}.$$

[6] See Wente, *Physical Review*, April, 1922.

In this expression, $\gamma$ is the adiabatic constant of air, $p_0$ the atmospheric pressure, $a_1$ the area of the fictitious diaphragm, and $v_1$ the volume of air in the film. This diaphragm is loaded externally by the air chamber, when the transmitter diaphragm is prevented from moving, by a stiffness reactance of

$$M_1' = \frac{S_1}{jw} = \frac{\gamma p_0 a_1^2}{jwv},$$

in which $v$ is the volume of the air chamber. Similarly, the load of the air chamber on the transmitter diaphragm, whose area is $a_2$, is

$$M_2' = \frac{S_2}{jw} = \frac{\gamma p_0 a_2^2}{jwv}.$$

The air chamber also acts as a mutual impedance between the thermal unit and the transmitter diaphragm equal to

$$M_{12}' = \frac{S_{12}}{jw} = \frac{\gamma p_0 a_1 a_2}{jwv}.$$

If, further, the intrinsic impedance of the transmitter diaphragm, which may be any function of frequency, be denoted by $Z_2$, the equations of motion of the system may be written

$$F = (Z_1 + M_1')\,\dot{x}_1 - M_{12}'\,\dot{x}_2,$$
$$0 = -\,M_{12}'\,\dot{x}_1 + (Z_2 + M_2')\,\dot{x}_2.$$

In these equations, $F$ is the force acting on the thermal receiver "diaphragm" due to alternating current, $\dot{x}_1$ the velocity of its motion and $\dot{x}_2$, the velocity of motion of the condenser transmitter diaphragm.

A rough calculation shows that $v_1$ is very small compared with $v$, so that $S_1$ may be neglected compared to $s_1$ and that the reaction $M_{12}'\dot{x}_2$ may be neglected. The analysis of the condenser transmitter shows $Z_2$ to be very large compared to $M_2'$. These equations may then be rewritten

$$F = Z_1\,\dot{x}_1,$$
$$M_{12}'\,\dot{x}_1 = Z_2\,\dot{x}_2. \tag{1}$$

The equations of motion, when the receiver is inserted in the ear, may be derived in a similar way. In this case, although the volume of air between the receiver and ear drum is the same as before, the walls may yield appreciably, particularly in some frequency ranges. The mutual impedance between the receiver and ear drum, is, therefore, not necessarily a simple stiffness reactance. Also the loads due to it on the thermal receiver and ear drum, which in this case takes the place of the transmitter diaphragm, are not simple stiffness reactances. The constants in the case of the ear system will be denoted by the same letters as those used in the calibration but with the primes dropped, with the exception that the intrinsic impedance of the ear drum is denoted by $D$. $D$ includes the reactions of the ossicles of the middle ear and the cochlea and is probably a complicated function of frequency. If, as may be expected, nature's design is efficient, then $D$ must be of the same general order of magnitude as the load on the ear drum, $M_{12}$, of the ear canal. This probably constitutes the largest difference between the calibration and the observational systems. Strictly, of course, the condition for maximum power absorption by the ear drum from the air is that $D$ be the conjugate of the impedance of the load on it due to the unobstructed ear canal. This condition is not obtained in nature because of such requirements placed on the design as protection from injury, etc.

In the case of the ear, $M_1$ may again be neglected, compared to $Z_1$, and the reactance, $M_{12}\dot{x}_2$ may be neglected. Then

$$\begin{aligned} F &= Z_1 \dot{x}_1, \\ O &= -M_{12}\dot{x}_1 + (D + M_2)\dot{x}_2, \end{aligned} \tag{2}$$

where $\dot{x}_2$ represents the velocity of motion of the ear drum. Suitable variations with frequency are implied in each of the "constants" of this system.

We are now in a position to see just what has been measured and called, for the sake of brevity or want of a better name, "minimum audible pressure" in the first part of this paper.

Let $\dot{x}_1$ now represent the velocity of the receiver diaphragm in both systems corresponding to that necessary to obtain a minimum audible sensation in the ear, and $F$ the corresponding force. Then $\dot{x}_2$ will be the velocity of the ear drum corresponding to minimum audibility in equation (2). In the calibration, the pressure $p'$ on the condenser transmitter diaphragm corresponds to $\dot{x}_1$. The total force acting on this diaphragm is $p'a'$ where now $a'$ designates its area. Since this force is relieved by the motion of the diaphragm, it is seen from equation (1) to be equal to

$$p'a' = M'_{12}\dot{x}_1. \tag{3}$$

Similarly if the actual pressure on the ear drum is $p$, and its effective area, $a$, the total force on the ear drum $pa = D\dot{x}_2$. Combining equations (2) and (3) gives

$$p' = \frac{a}{a'}\frac{M'}{M}\left(\frac{M_2\dot{x}_2}{a} + p\right), \tag{4}$$

or

$$p = p'\frac{M}{M'}\frac{a'}{a} - \frac{M_2\dot{x}_2}{a}. \tag{5}$$

The pressure $p$ is the actual pressure on the ear drum. The pressure $p'$ is that measured and plotted in the diagram. If the walls of the ear canal and the ear drum were unyielding, $p$ and $p'$ would be identical for then $M = M'$ and $M_2\dot{x}_2/a$ would vanish. If the yield of the ear canal walls were such as to relieve half the pressure in the canal and that of the ear drum about the same, the difference would be considerably less than one of the divisions, in the diagrams, on the intensity scale. If the drum impedance $D$ should be found to be negligible compared to its load $M_2$ the difference would be considerable. This, however, is hardly to be expected even through narrow ranges of frequency. If the impedances in the formulas were measured the energy flow into the ear drum could be computed.

In conclusion, the present status of the ear problem may be summarized. The philosophy of external ear dynamics has been touched on but there still remain difficult problems both theoretical and experimental. A start has been made on a sound basis in the explanation of the action of the cochlea by Roaf, "Analysis of Sound Waves by the Cochlea," *Philosophical Magazine*, February 1922. Nothing dependable has as yet been published on the action of the middle ear for audio frequencies. It is usually assumed that the various parts undergo relative displacements at audio frequencies in the same way as they react to static forces but this is very likely far from the truth.