ACOUSTICS

IT HAS BEEN my good fortune to be associated with the Board of Governors of the Institute of Physics most of the time from its organization and therefore I know the progress that has been made since the founding of the Institute. Many important things have happened during those twenty years, both in science and in our national and international affairs. Although we seem to make little or no progress in learning how to live together peaceably, these twenty years have been brilliant ones for scientific achievement.

It is an honor to be asked to represent the field of acoustics on this program today. I will first give a few of the headlines in the general field of acoustics and then give in more detail some of the recent developments in the dynamics of the hearing mechanism.

During the latter part of the last century, two great names stand out in the field of acoustics, Rayleigh and Helmholtz. Rayleigh, in his two classical volumes, set up the fundamental equations for solving all theoretical problems in acoustics in the same sense that Maxwell did for all electromagnetic problems. Although the first edition of his book appeared in 1878, it is still widely used today by students of theoretical acoustics. Helmholtz, on the other hand, was an experimenter and laid the ground work for the field of psychoacoustics, and has always been an inspiration to those working in this field.

Before the invention of the vacuum tube, there were only a few scientists in this country doing research work in acoustics. Sabine was doing his pioneering work in room acoustics. D. C. Miller was working out his beautiful experiments with the phonodeik and musical instruments. G. W. Stewart and associates were working with acoustic filters and binaural effects. Webster was toying with his experimental phone for measuring absolute values of sound pressure.

The advent of the vacuum tube not only brought a new measuring tool which made possible accurate acoustical measurement, but it also brought three new industries into public use, namely, radio broadcasting, sound pictures, and long distance telephony. These fields required a large increase in personnel trained in acoustics. So it was not long after this epoch-making invention that many persons were urging the organization of an Acoustical Society. The organization was accomplished in 1929. This sudden growth in acoustical workers is illustrated by the fact that only one or two papers per year appeared in the first quarter of this century, whereas in the second quarter more than fifty papers per year were given and printed in the Journal of the Acoustical Society. At first, the emphasis was upon architectural acoustics, but it was not long before there was a well-balanced program of research in other fields of acoustics.

In architectural acoustics, this revived interest started with Sabine's famous formulae for reverberations in a closed room,

$$t = .05\frac{V}{S\alpha}, \tag{1}$$

where t is the reverberation time, or time for the sound to decay 60 db, V the volume of the room in cubic feet, S the area of the walls in square feet, and α the average absorption per square foot. During the first year of the existence of the Acoustical Society, this was modified by Eyring and Norris to be

$$t = \frac{.05\,V}{-S\log_e(1-\alpha)}. \tag{2}$$

Then followed many papers on how best to measure the absorption coefficient α. Different observers did not agree on the value of the absorption coefficient for the same material. This controversy went on for many years as the *theory* of room acoustics slowly developed through the efforts mainly of Morse, Knudsen, Bolt, Beranek, London, and others. The modern equations representing the acoustical conditions in a room are about as complicated as those representing the probability of an electron being at a certain position with respect to the nucleus of the atom at a certain time. Indeed, the equations are very similar. There are an infinite number of natural frequencies in a room. The amplitude and phases of the frequencies excited by a given driving force are dependent in a known way upon the boundary conditions—that is, the dynamical conditions at the walls. Instead of defining these conditions in terms of a certain number of absorption units, the acoustical impedance of the surface is given in amplitude and phase. Methods are now available for handling this complicated phenomenon and in a way that

Six invited papers were presented during the major symposium of last October's meeting of the AIP and its Member Societies, of which this is the second to be printed in *Physics Today*. Articles based on talks by Drs. Condon, Fermi, Slater, and Land will appear in later issues.

By Harvey Fletcher

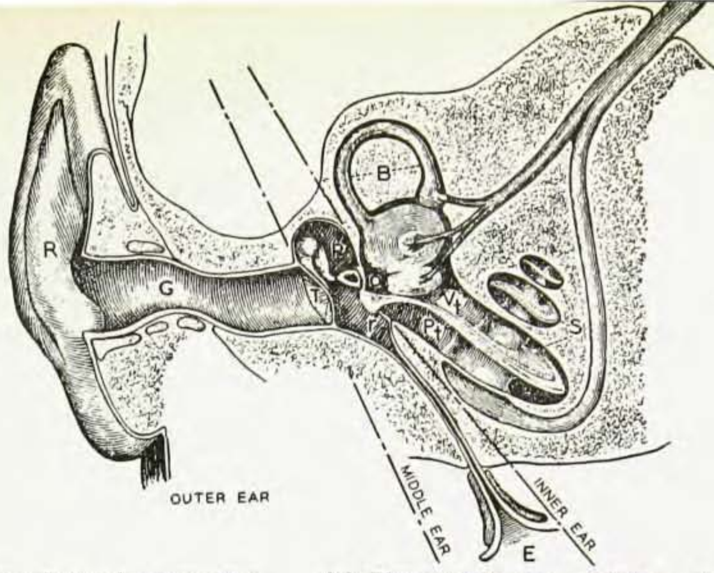


Fig. 1

permits one to specify the proper design for any given acoustical effect.

Similar progress has been made in understanding the transmission of sound through partitions. In the beginning, it was thought that the walls vibrated with the sound wave and so the heavier it was made, the smaller would be its amplitude, and hence the smaller the transmission. So heavy walls were used for insulating rooms against outside sounds. These heavy walls certainly were good insulators, but their cost and weight were very great.

Although the fundamental theoretical basis for the transmission of sound through multiple layers of different acoustical materials was set by Rayleigh, it is only recently that it is beginning to be understood by engineers working in this field. If one chooses the thicknesses and acoustical constants correctly, one can obtain a great variety of transmission characteristics. For a single frequency, one can make the wall perfectly transmitting or perfectly opaque. By choosing the right combinations of such layers, one obtains band-pass and band-elimination filters and various combinations of these.

In the early twenties, the fundamental acoustical equations were successfully applied to the design of telephone microphones and receivers and loud speakers. Wente was the pioneer and one of the principal contributors in these fields. With these instrumentalities, it was mainly an engineering development to produce transmission, recording, and reproducing systems that would produce little or no distortion in the transmitted sounds.

In musical acoustics, except for systems for recording and reproducing music, the progress has been slow. On the engineering side, there have been a number of electronic organs designed and built. These are widely used, so you are familiar with them. In my opinion, there is some very fruitful research to be done here. But it needs a cooperative effort of musicians, psychologists, physicists, and engineers.

In the field of psychoacoustics, there has been great progress, and I wish to speak in greater detail about part of this field, namely, hearing. Excellent instrumentalities are now available for doing research with the speech sounds.

(1) Phonographs are available, which will record and reproduce the sounds with little or no perceptible distortion. The new magnetic type is very useful, since it can be cut and spliced like ordinary motion picture film and thus the time sequence of the speech sounds can be changed in any desired way. It is made by coating a medium like paper or scotch tape with a magnetic oxide. If a photographic film is used, the wave form can be viewed and studied.

(2) Sonographs are available, which will record a sample of speech and then analyze it and plot a graph showing time as the abscissas, frequency as the ordinates, and intensity by degree of blackness.

(3) An experimental device is available for imitating any of the vowel sounds and their various shades of quality by changing only three parameters. This promises to be a big help to phoneticians. Instead of depending upon expert phoneticians whose judgments may differ, for describing a spoken vowel it can be imitated and then described by these three numbers. These three numbers correspond roughly to the resonant frequencies of the mouth cavity, the throat cavity, and the coupling between them, respectively.

Mathematical relations are now available for predicting how well one person, called the listener, will recognize the speech sounds of another person, called the speaker, in terms of the physical constants of the medium transmitting the sounds and the practice coefficients of the speaker and listener.

These equations are no doubt related to the information theory equations which have created so much excitement in the communication field during the last few years, but the connection has not yet been made. One of the many startling conclusions coming from this information theory is that a transmission system having a bandwidth of only 10 cycles and a signal-to-noise ratio of about 40 db will transmit the information contained in spoken speech as fast as an average talker speaks.

These few headlines give a general view of the field of acoustics. Now I want to cover in more detail some recent work on the dynamics of the hearing mechanism.

Harvey Fletcher, who until his retirement had served as director of physical research for the Bell Telephone Laboratories for more than thirty years, is a past president of both the Acoustical Society of America and the American Physical Society.

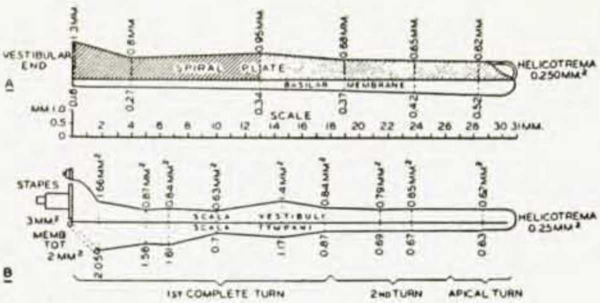


Fig. 2

YOU ARE FAMILIAR with the gross anatomy of the ear. It is shown in Figs. 1 and 2. Sound waves in the air are conducted down the external auditory meatus to the tympanic membrane. This then communicates the vibration to the three bones of the middle ear, which may be considered as a mechanical transformer converting the pressure variations in the air to pressure variations in the liquid of the inner ear. For a long time it has been considered that this transformer matched the impedance of the air to that of the water and consequently amplified the pressure variations 60-fold or by 35 db. However, recent measurements by Bekesy on actual specimens of the human ear have shown that this is far from the truth. In Fig. 3 are

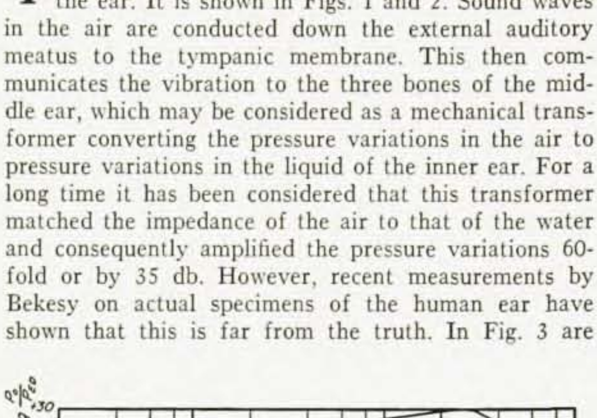


Fig. 3

shown the results of these measurements. The top curve is for the case when the impedance looking away from the stapes into the inner ear is infinite. This would approximate the case where the containing walls of the inner ear fluid were unyielding. But in an ear under normal operating conditions, the basilar membrane separating the scala vestibuli from the scala tympani is very flexible, so instead of the impedance looking away from the stapes being infinite, it is almost zero for the lower frequencies. One can deduce from Bekesy's measurements what the amplification ratio will be under the actual operating conditions and it is given by the lower curve. It is seen that this mechanical transformer is a very poor one, having properties somewhat like those found in cheap radio sets. There is no amplification for frequencies below 600 cps but large attenuations, especially for the very low frequencies. It approaches the case of infinite impedance only at frequencies as high as 10,000 cps. But it is important to notice that there *are* amplifications for the important range of speech frequencies. It is mainly due to the poor performance of this mechanical transformer that the acuity of hearing becomes so much less at the low than for the middle range of frequencies. It seems to me these recent findings should have an important bearing on the fenestra operations to improve hearing which are frequent these days, but I cannot pursue this subject further here.

The dynamical behavior of the cochlea has recently been deduced from the fundamental hydrodynamical equations and known constants of the ear and it agrees with the beautiful experimental results of Bekesy. In Fig. 4 is shown a diagrammatic sketch of the inner ear.

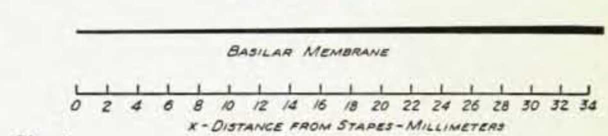
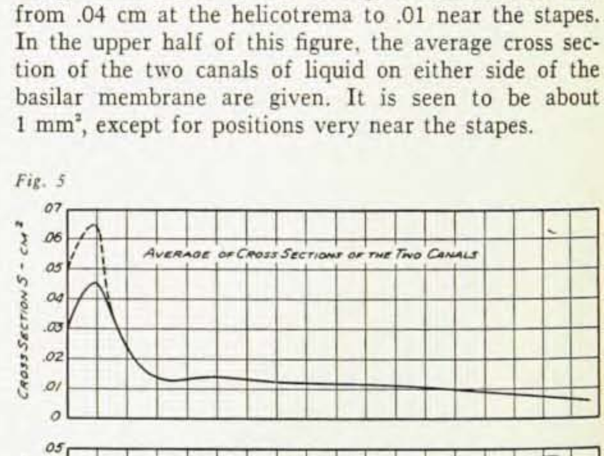


Fig. 4

The problem is to find the amplitude and phase of the basilar membrane at all positions along its length when a sinusoidal variation of pressure, $P_0 \cos \omega t$, is impressed at the stapes end.

To solve this problem, it was necessary to make certain approximations which were as follows. Since the length of basilar membrane is nearly 100 times its width, it was assumed that it could be broken up into small square vibrating units, the side of the square being equal to the width b of the basilar membrane. The values of b at different distances from the stapes are given in the lower half of Fig. 5. It is seen to vary from .04 cm at the helicotrema to .01 near the stapes. In the upper half of this figure, the average cross section of the two canals of liquid on either side of the basilar membrane are given. It is seen to be about 1 mm², except for positions very near the stapes.

Fig. 5



Now the force driving each of these little elemental vibrators is Pb^2 where P is the pressure difference on the two sides of the element plus forces exerted by adjacent elements. It will be assumed that these latter forces can be neglected in comparison to the former. If then m is the mass of the element, s the stiffness constant, and r the mechanical resistance, the average velocity $\bar{v}$ of this little elementary area of the basilar membrane is given by

$$\bar{v}=\frac{1}{2}\frac{Pb^2}{j\left(m\omega-\frac{s}{\omega}\right)+r}=\frac{1}{2}\frac{Pb^2}{Z_m}, \tag{3}$$

where Z_m is the mechanical impedance of the little element. The numerical factor ½ is only approximate and is to take care of the fact that the two edges are held so that they cannot move.

Let x be the position coordinate or distance in cm from the stapes end of the basilar membrane to the little element under consideration. The problem then is to find how P, m, s and r vary with x, and then apply this equation to find $\bar{v}$. The displacement $\bar{y}$ is given by

$$\bar{y}=\frac{\bar{v}}{j\omega}. \tag{4}$$

The radiant mass, that is, the amount added due to the area b^2 being immersed in a liquid like water, can be calculated from acoustical equations and is approximately equal to b^3. This is equivalent to adding a layer of liquid $1/2b$ high on either side of the element. The mass of the membrane itself and the structures which vibrate with it was estimated from anatomical data to be $.75b^3$. So the total mass of the little element is

$$m=1.75b^3. \tag{5}$$

As you will remember, b was given as a function of x, so m is known as a function of x and is shown in Fig. 6. Bekesy measured by a very ingenious method the stiffness constant at three positions along the basilar membrane, with the result shown by the three points of Fig. 6. The straight line was considered to represent approximately the values of the stiffness s. The values of m are also shown in this figure. Now the resonant frequency of each element is then given by

$$f_0=\frac{1}{2\pi}\sqrt{\frac{s}{m}}, \tag{6}$$

and is shown in Fig. 7. The circles and crosses are observed data by Bekesy of the position for maximum displacement of the basilar membrane for the various frequencies shown. The solid dots give the calculated position for maximum displacement. Due to damping, it is always shifted to the left of the position for the resonant frequency.

The mechanical resistance can be calculated from measurements of Bekesy and it turns out to be given by

$$r=.5m\omega_0. \tag{7}$$

It is convenient to rewrite equation (3) as follows,

$$\bar{v}=\frac{j}{\omega}\frac{P}{3.5b}\frac{1}{\left(\frac{f_0}{f}\right)^2-1+j.5\frac{f_0}{f}}, \tag{8}$$

and the displacement

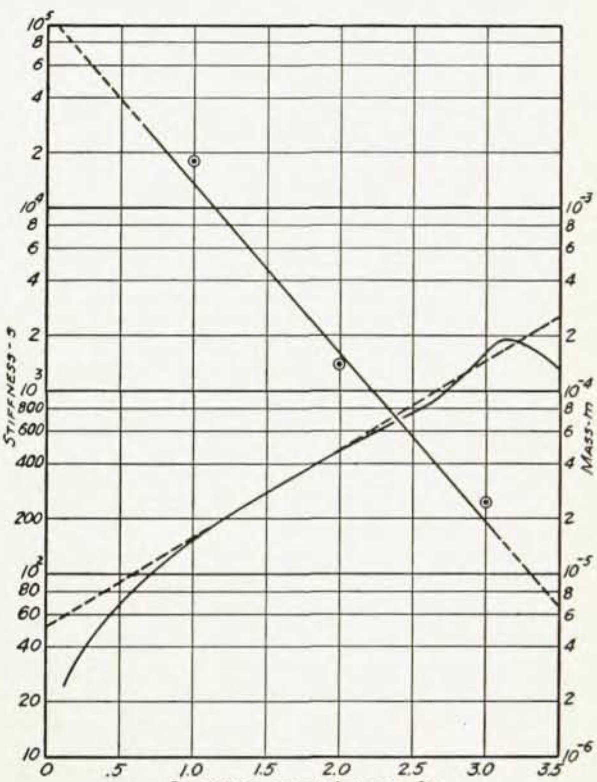
$$\bar{y}=\frac{1}{\omega^2}\frac{P}{3.5b}\frac{1}{\frac{f_0}{f}-1+j.5\frac{f_0}{f}}. \tag{9}$$

To find how P varies with the position of the element, one proceeds as follows. The usual hydrodynamical equations of continuity and force are set up for a little element of liquid in the scala vestibuli. Then a similar set of equations is derived for the scala tympani. When these are combined, the following equation is derived,

$$\frac{1}{Q}\frac{\partial^2(SP)}{\partial x^2}+k^2(SP)-2\rho b\frac{\partial\bar{v}}{\partial t}=0, \tag{10}$$

where Q is a quantity which depends upon the viscosity of the liquid of the inner ear and approaches unity when the cross section of the canals departs from capillary size, and ρ is the density of the liquid which will be considered unity, and S is the average cross section of the two canals, and k is the usual wave constant equal to 2π divided by the wavelengths of a sound wave in the liquid.

Fig. 6



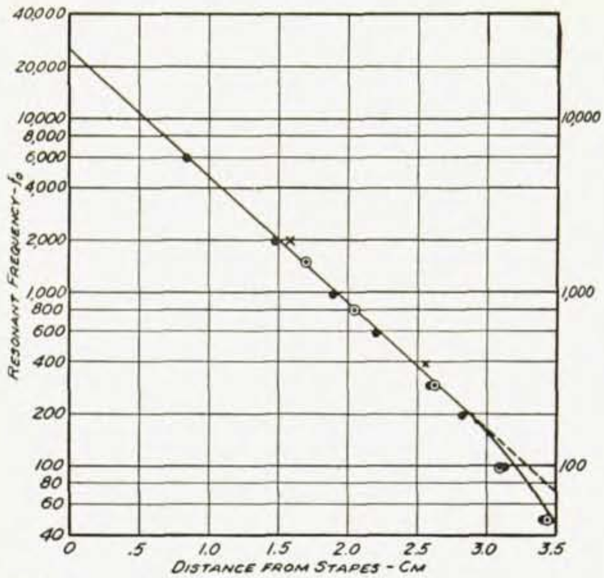


Fig. 7

If this equation is combined with (8) to eliminate $\bar{v}$, the following differential equation of SP and x is derived,

$$\frac{1}{Q}\frac{\partial^2(SP)}{\partial x^2}+k^2(SP)+\frac{1}{1.75S}\frac{SP}{\left(\frac{f_0}{f}\right)^2-1+j.5\left(\frac{f_0}{f}\right)}=0, \quad (11)$$

from which the values SP at each position x can be calculated. Since P is in general a complex quantity, this single equation is equivalent to two others having only real quantities. If the basilar membrane were infinitely stiff, then the last term would be zero, and for tubes of reasonable size where $Q=$ unity, what is left is the usual wave equation describing a sound wave being propagated through the liquid of the two tubes. However, if numerical values of f and f_0 and S are substituted, it will be found that the second term is negligible compared to the third term. This is equivalent to saying that the propagation velocity of the sound wave is very much greater than the velocity of propagation of the wave along the basilar membrane and that the fluid in the inner ear may be considered incompressible when dealing with this problem. So any displacement of fluid by the stapes is immediately registered as a displacement of fluid at the round window. Also, the fluid displaced by the basilar membrane is the same as that displaced by the stapes except for frequencies below 200 cycles when some of the fluid goes through the helicotrema.

A general solution of (11) has not been found, so numerical integrations were made for various impressed frequencies. The boundary conditions are at $x=0$

$$SP=S_0P_0,$$

where S_0 is area of stapes and P_0 pressure difference in liquid at the stapes from that at the round window. Also, at $x=3.5$ cm, which is the length of basilar membrane, the pressure difference across the basilar membrane is the same as the pressure drop through helicotrema which is capillary in size (.2 or .3 mm in diameter). It can be shown that this condition leads to the following boundary condition, namely

$$\frac{\partial(SP)}{\partial x}=-8(SP). \quad (12)$$

The numerical factor is derived from the relative dimensions of the helicotrema and the cross sections S, and the viscosity coefficient, and may vary for different specimens of ears by more than 100 per cent. This is also equivalent to two equations involving only real quantities.

It is not appropriate to present the details of the calculation here but only the results.

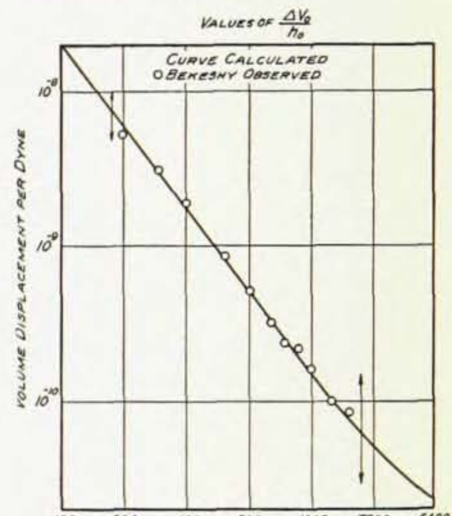
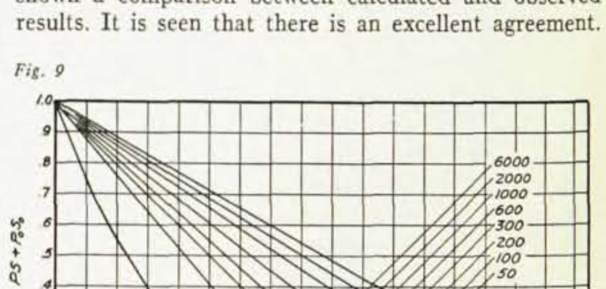


Fig. 8

These equations permit one to calculate the volume of fluid displaced by the stapes when one dyne difference in pressure exists in the fluid in front of stapes from that in front of the oval window. In Fig. 8 is shown a comparison between calculated and observed results. It is seen that there is an excellent agreement.

Fig. 9



In Fig. 9 is shown the calculated pressure distribution at different positions. The ordinates give the ratio of $PS \div P_0S$, and the abscissas the distances from the stapes. For canals of uniform cross section, these curves would give the actual amplitude of pressure variation. The vertical arrows show the position for the resonance frequency. The phases were also calculated but are not shown in this figure. They vary from 0 at $x = 0$ to approximately π at the resonance position. It is seen that at 50 cps there is an appreciable pressure across the helicotrema and consequently liquid is forced back and forth through it which adds to the damping of the little vibrating elements of the basilar membrane in this region, and this was taken into account in the calculations. For frequencies above 100 cps, this pressure is negligibly small, and the wave motion can be considered as stopped 2 or 3 mm beyond the resonant position.

In Fig. 10 are shown the relative amplitudes and

Fig. 10

phases of vibration of the basilar membrane at different positions. The solid lines are calculated and the points are taken from Bekesy's experimental data. The crosses and circles are from one specimen and the squares are from another one taken about two years earlier. It is seen that for high frequencies the maximum displacement is near the stapes and for low frequencies it is near the helicotrema. For frequencies below 50 cps the curves are similar to that for 50 cps, becoming flatter as the frequency gets lower. Remember, these curves show the amplitudes. The actual displacement of the basilar membrane at any one time is not like these curves. For a 200 cps tone, and at six different times separated by ⅛ of a period, the displacements are shown in Fig. 11. The time zero is taken when the membrane is at its maximum displacement. However, it turns out that at this time and this frequency, the total displacement of the fluid is almost zero. This follows, because that part of the area enclosed by the curve and the zero axis which is above this axis is approximately

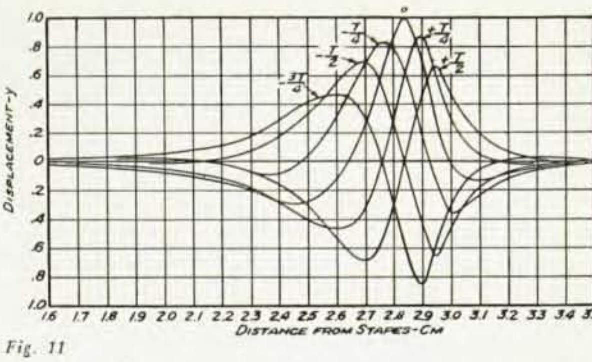


Fig. 11

equal to that below this axis. Since the liquid may be considered incompressible, this means at this time the stapes is at its equilibrium position. At a time $T/4$ earlier it was at its position for maximum displacement, and this corresponds to the curve marked $-T/4$. Then this curve should show a maximum total displacement, and it does.

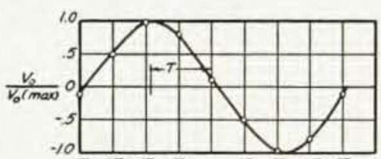


Fig. 12. Time: $\frac{T}{8}\frac{5}{8} \times 10^{-3}$ Sec. 0 is time when y_m occurs. v_0 max occurs 1.2×10^{-3} seconds earlier and is equal to .08 $b_m y_m$.

A plot of the total displacement versus time as integrated from these curves is given in Fig. 12. It is seen to be sinusoidal, as it should be. The time of the wave to travel from the stapes $x = 0$, to $x = 2.84$, the position for maximum displacement for a 200 cps tone, is approximately $T/4$ or equal to 1.25 milliseconds. The above equations permit one to calculate the travel time from the stapes to any position, and the calculated times are shown in Fig. 13. The circles give Bekesy's observed results. It is seen that the speed of travel of the wave is very much faster near the stapes where the membrane is very stiff and slows down very much near the helicotrema where the stiffness of the membrane is very much reduced. For example, the average speed for th first 8 mm is 26 meters per second, while for the last 8 mm it is only 6 meters per second.

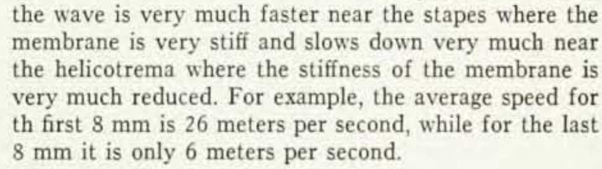


Fig. 13

The values of the displacement amplitudes in Fig. 10 are relative, but the absolute values can be calculated. The maximum displacement and velocity amplitudes for one dyne pressure in the air in front of the eardrum are shown in Fig. 14. The ordinates are db from 1 cm and db from 1 cm/sec. It is seen that the displacement amplitudes per dyne are approximately constant from 100 to 2000 cps while the velocity amplitudes fall off almost inversely proportional to the frequency in this same range.

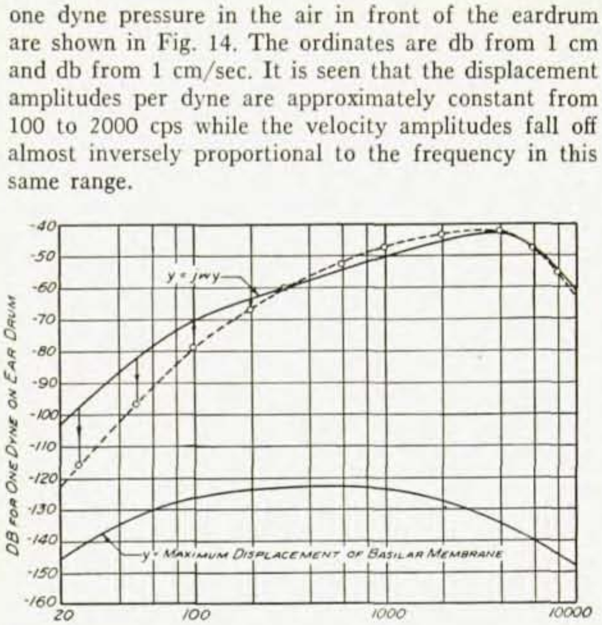


Fig. 14

It is interesting to calculate the maximum amplitudes of displacement and velocity of the basilar membrane when pure tones of various frequencies are impressed upon the ear at intensities which are just perceptible. Such pressures in front of the eardrum have been measured, and so the displacement and velocity amplitudes were calculated to be those shown in Fig. 15. First, let me call your attention to the very minute displacement of the basilar membrane that will be detected by the average ear. At 1500 cps it is only 10^{-9} cm or about $\frac{1}{10}$ the diameter of the hydrogen molecule. Next, it is evident that at the threshold the velocity is more nearly constant at various frequencies than the displacement, the latter varying over a range of 1000 to one, while the former has a range of about 5 to one.

The variation of acuity of hearing with frequency can be explained by three simple assumptions. Namely, at pressure levels corresponding to the threshold of hearing, the number of nerve discharges per second coming from a unity length of the basilar membrane is proportional: (1) to the energy of vibration or $\bar{v}^2$ at the position x; (2) to the density σ of the nerve endings at the position x; and (3) to the impressed frequency for frequencies below 300 cps to a constant for frequencies above 300 cps.

These are all reasonable assumptions which one might expect to hold. The last one comes from the action of auditory nerve fibres. For frequencies below 300 cps, the nerve is excited only at the minimum and at maximum velocity and consequently the number of discharges are proportional to the frequency. The discharges are in synchronism with the frequency. The nerve fibre cannot discharge faster than 300 times per second. So, above this frequency the discharge rate is independent of frequency. Putting these assumptions into an equation, we have the loudness N of a sound expressed in sones given by

$$N = K\frac{f}{300}\int_0^{3.5} \bar{v}^2\sigma dx = 5\times 10^5\frac{f}{300}\int_0^1 \bar{v}^2 dZ, \quad (13)$$

where K is a constant which was evaluated to be 5×10^5 from the condition that N must be 10^{-3} sones at the threshold. The quantity

$$\sigma dx = dZ$$

is the fraction of the total nerve endings which are in the elemental length dx. Also, it must be remembered that above 300 cps the quantity $f/300$ must be taken as unity. Using the curve of Fig. 15 for values of $\bar{v}^2$ and the curves of Fig. 10 for relative values of $\bar{v}$, the following values of 10 log N and N were calculated from equation (13) to be the threshold values of N for the frequencies indicated.

f	$10 \log N$	N (*millisones*)
25	− 31.3	1.3
50	− 32.2	1.6
100	− 27.7	.6
200	− 29.2	.8
300	− 30.5	1.1
600	− 30.8	1.2
1000	− 31.2	1.3
2000		
6000	− 27.7	.6

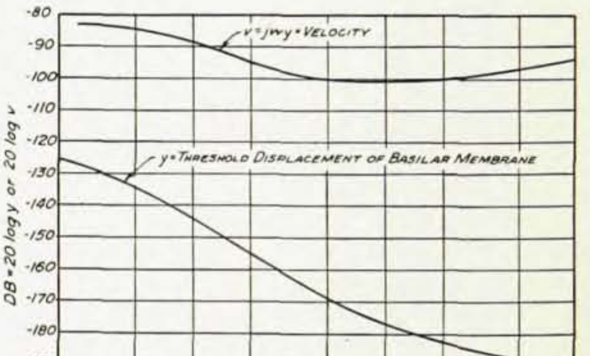


Fig. 15

If the assumptions above were correct, the values of N in the last column should be 1 millisone. It is seen from column 2 that the variations from this value are less than ± 3 db, which is well within the experimental error of measuring the threshold of hearing pressure levels. So one concludes that the above assumptions adequately account for the variation of acuity of hearing with frequency. So it is seen that the dynamical behavior of the hearing mechanism about which there has been so much speculation in the past is now placed on a very firm basis, both theoretically and experimentally, and leaves little room for further speculation.