Acoustical Instruments *

By E. C. WENTE

Previous to the development of amplifiers most of the instruments used in acoustical research depended for their operation upon purely mechanical principles. This paper includes a brief survey of such of these instruments as are still of interest in connection with the investigation of technical or research problems in acoustics, but it deals primarily with the more recent electrical devices used in the study of air-borne sound waves.

The limitations and fields of application of various electrical instruments, including microphones, particularly adapted to definite types of acoustic measurements, are discussed.

MEASUREMENTS in acoustics may be said to date from the fifth century B.C., when Pythagoras observed that the lengths of strings giving the fifth, the fourth and the octave had the ratios 6 : 4 : 3, but no further really significant quantitative acoustic measurements were reported until the 17th centry when the frequencies of vibration of the notes in the musical scale were determined by Mersenne.[1] The first systematic treatise on experimental acoustics was published by Chladni [2] whose work on the vibration of plates and diaphragms is well known. With respect to the development of present day acoustical instruments the most outstanding contribution of the last century was the application of diaphragms for receiving sound waves by Scott and Koenig. Such diaphragms not only are used in most of these instruments, but also form an important element in two notable inventions of the last century, the telephone and the phonograph.

One of the chief functions of an acoustic diaphragm is to translate the extremely small pressures of sound waves into comparatively large corresponding forces, but a diaphragm cannot deliver more power to a system than it absorbs from the sound field. Telephony over comparatively long distances was made possible by the invention of the carbon microphone, an instrument which is capable of translating the small powers of acoustic diaphragms into relatively much larger electrical powers. This microphone, while of great commercial utility, was, for a number of reasons, unsuited for most quantitative acoustic measurements. Practically all shackles were removed from

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[1] *Harmonie Universelle* (1636).

[2] *Die Akustik* (1802).

the designer of acoustical instruments some twenty years ago through the invention of the vacuum tube telephone amplifier. Previously his chief concern lay in making a device sufficiently sensitive to give a measurable response; now sensitivity became of secondary importance, and attention could be focused on the design of instruments which should be capable of performing their function without distortion.

As a result of this invention, instruments depending upon an amplifier for their utility have come so to dominate the field of acoustic measurements that we might easily be led to disregard all others. A number of such other instruments have, however, in recent years been brought to a high state of development which are peculiarly suited either for the calibration of other devices, or for the study of certain special problems. This paper attempts to give a brief critical survey of the various types of acoustical instruments which at the present time are finding applications in technical fields and in acoustical research studies.

GENERAL PRINCIPLES

The Rayleigh Disc

That under certain conditions a torque is exerted on a thin disc suspended by a fine fibre in a stream of air was first observed by the late Lord Rayleigh,[3] who recognized in this phenomenon a means for measuring the intensity of sound.

The following quantitative relationship between the torque and the stream velocity was derived by W. Koenig:[4]

$$\tau = \frac{4}{3}\rho_0 r^3 u^2 \sin 2\theta,$$

where ρ_0 is the mean density of the medium, r the radius of the disc, u the stream velocity, and θ the angle between the undisturbed stream and the normal to the disc. The assumptions underlying the derivation of this formula are that the fluid is incompressible, that the disc is an infinitely thin ellipsoid and that there are no forces due to viscosity or to discontinuities of flow at the edges of the disc; i.e., the velocities are derivable from a potential. In view of these assumptions how far may we rely on the above formula in applying it to a suspended plane flat disc as commonly used for measuring the particle velocity of a sound wave, where none of these assumptions are strictly fulfilled? In most acoustical problems it is perfectly safe to assume a potential field as the forces due to viscosity and eddies are of the

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[3] *Phil. Mag.* **14**, 186 (1882).

[4] *Wied. Ann.* **43**, 43 (1891).

second order. With respect to the torque on the Rayleigh disc it is not so obvious that such forces may be neglected as the potential torque is itself of the second order. The effects of discontinuities in the flow at the edges and of viscosity have not been determined theoretically. To what extent these are negligible can be found out only by experiment. Strictly speaking we therefore cannot regard the Rayleigh disc as an absolute means for determining sound intensities, as is often implied. A number of experiments have been carried out to determine the accuracy of the Koenig formula. Koenig himself, in a subsequent paper,[5] made an estimate of the effect of the discontinuous flow at the edges and reported measurements of the torque exerted on a flat disc when placed in a steady stream of air of known velocity. As a result of these studies he came to the conclusion that the application of his simplified formula to the Rayleigh disc did not provide a reliable and simple method for measuring the absolute value of sound intensity. He felt that the effect of viscosity would probably also have to be taken into account. However, Koenig's experiments were made under difficult conditions and it is possible that his measurements were affected by eddies in the air stream.

Greater confidence in the accuracy of Koenig's formula is derived from the experiments of Zernow.[6] Zernow experimented with both thin true ellipsoids and flat discs; these were placed in a box attached to one prong of a tuning fork, the motion of which was observed microscopically. The tuning fork was driven at a frequency of 92 c.p.s. and the relation between the amplitude of motion and the resulting deflection of the disc was determined. The values so found for the ellipsoids agreed remarkably closely with those computed by the formula. For the discs the agreement was within about 10 per cent. On the basis of the values so found Zernow proposed an empirical correction factor which reduces to unity for infinitely thin discs. Barnes and West,[7] using thinner discs, made measurements similar to those of Zernow. They found almost perfect agreement between the experimental and the theoretical values. They were able to show also, by measurements made at audio frequencies with discs of different diameters, that the torque varied as the cube of the diameter, provided first, that the diameters did not exceed 1/5 wave-length, and second, that the discs were sufficiently rigid to be free from resonant vibrations at the measuring frequency. Mallet and Dutton [8] found that the torque was proportional to the square of the velocity up to

[5] *Wied. Ann.* **50**, 639 (1893).
[6] *Ann. d. Physik* **26**, 79 (1908).
[7] *Jour. I.E.E.* **65**, 871 (1927).
[8] *Jour. I.E.E.* **63**, 502 (1925).

velocities of 5 cm. per second. We might, however, expect that a torque resulting from discontinuous stream flow at the edges would be governed by a similar law.

No direct tests have been reported on the accuracy of the coefficient in Koenig's formula above 92 c.p.s., at which Zernow's measurements were made. However, sound intensities determined by the Rayleigh disc through the application of Koenig's formula have been found to be in good agreement with those determined with a microphone calibrated by other independent means. All the tests of the formula have been made with plane or spherical sound waves of moderate intensity. This fact should be borne in mind in order to guard against the use of the device under conditions where the formula may not be applicable. Such may be the case, for instance, where the sound intensity is very high. Measurements in non-uniform sound fields recently made by Kotowski [9] showed quite anomalous effects; in some cases the deflection was even in a direction opposite to that expected.

One great disadvantage of the Rayleigh disc method of measuring sound intensity, as ordinarily applied, is the fact that the disc will deflect under the action of a steady air stream. As the stream velocities in a sound wave are in any case quite small, circulating air currents may easily produce comparable deflections unless the instrument is well shielded therefrom. Under carefully controlled conditions measurements can be accurately made at sound intensities corresponding to pressures as low as one bar.

The effect of circulating air currents is greatly reduced in the method of measurement with the Rayleigh disc adopted by Sivian.[10] In this method the intensity of the sound to be measured is modulated at the source at a frequency of about 0.4 cycle per second. The disc with its suspension is proportioned so that its natural frequency is equal to this modulating frequency. The disc will then oscillate under the action of the modulated sound wave at an amplitude proportional to the square of the velocity. As circulating air currents generally have components lying below the modulating frequency they will have but little effect on the amplitude of the oscillations of the disc.

Determination of Intensity from Static Pressure Measurements

Another purely mechanical means for measuring sound intensity in absolute terms is based upon the fact that when radiant energy falls on a reflecting surface a static pressure is exerted on this surface, which in the case of sound is equal to [11] $((\gamma + 1)/2)I/c$, where I is the

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[9] *E.N.T.* **9**, 404 (1932).

[10] *Phil. Mag.* **5**, 615 (1928).

[11] Lord Rayleigh, *Phil. Mag.* **10**, 366 (1905).

intensity and c is the velocity of sound. A disc which just clears the opening in a plane baffle wall is attached to one arm of a torsion balance. From the deflection of the balance when sound falls at perpendicular incidence on the disc the radiation pressure and hence the intensity of the sound may be determined. This method has been successfully used in experiments with supersonic waves. At these high frequencies the diameter of the disc may be made a large fraction of a wavelength and the baffle may be omitted. At audio frequencies the necessity of using a baffle is a distinct handicap to this method.

Since the relation between pressure and condensation in air is not strictly linear a sound wave will, under certain circumstances, produce a change in static pressure. For a plane wave this has been shown by Thuras, Jenkins and O'Neil [12] to be equal to $-((\gamma + 1)/4) \times I/c$, where I is the sound intensity. Eichenwald [13] has suggested that a measurement of this pressure should provide a means for determining the absolute value of the sound intensity. Such increments in static pressure can, however, exist only when equalization by air flow to regions of normal pressure is precluded, a condition not easily established in practice.

Acoustic Valve

An extremely simple device for measuring sound intensities was devised by Kundt.[14] One end of a tube, which is placed in the sound field, is terminated by a valve which is so delicate that it will close during the negative and open during the positive half of the pressure cycle of the sound wave. The other end of the tube is terminated by a manometer. With perfect operation of the valve the sound wave will force air into the tube until the pressure indicated by the manometer is approximately equal to the maximum pressure in the sound wave. Recently Eisenhour and Tyzzer [15] have developed a sound meter operating on this principle. It is provided with an ingenious type of sensitive manometer with which the pressures are indicated on a dial. It has a fairly uniform sensitivity up to 2,000 c.p.s. The construction of the valve used in this meter is not disclosed in the literature. However, Ribbentrop [16] recently has described a similar sound meter in which the valve consists of the wing of a house-fly placed over an opening. It is stated that the instrument is capable of giving reliable measurements for sound pressures above 70 bars.

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[12] *Jour. Acous. Soc. Amer.*, January, 1935.
[13] *Rend. Sem. Mat. e Fisico d. Milano*, Vol. 6 (1932).
[14] *Ann. d. Physik* **134**, 568 (1868).
[15] *Jour. Franklin Inst.* **208**, 397 (1929).
[16] *Zs. f. Tech. Phys.* **13**, 396 (1932).

Measurement of Periodic Changes in Density

As the optical index of refraction of an elastic medium depends upon the density, it is possible to measure sound by letting one of the paths of the light beams of an interferometer pass through the sound field while the other is shielded therefrom. The interference fringes of the interferometer will be displaced periodically in synchronism with the periodic variations in density of the wave. This method was first used by Boltzmann and Toepler[17] who in this manner observed the rather large variations in density within a sounding organ pipe. This method has the advantage that the measurements are independent of frequency but it is not very sensitive and at best is rather cumbersome. An interesting modification[18] of this method has recently been applied in measurements of high-frequency sound waves in liquids. At these high frequencies the wave-lengths are so small that the spatially periodic variations of the density of the medium can act as a diffraction grating for light waves. This phenomenon has provided a neat means of picturing the propagation of high-frequency sound waves in liquids.[79]

Instruments Employing Diaphragms and Optical Magnification

In the phonautograph of Scott (1857) a circular diaphragm is actuated by sound waves and the motion is recorded on a moving strip of smoked paper by a stylus attached to the center of the diaphragm. The recorded amplitudes are no greater than the actual amplitudes of motion of the diaphragm which, except at the resonance frequency or for very intense sounds, are so small that they cannot be accurately determined from the record. Small motions can be observed and recorded if the stylus is replaced by an optical lever. This arrangement in various forms has been used in the past by a number of investigators. It reached its highest state of development in the well-known phonodeik of D. C. Miller.[20] In this instrument a horn is used for increasing the sound pressure acting on the diaphragm, the motion of which is magnified in some forms of the instrument by as much as 40,000 times. By refinements in mechanical design and construction a remarkably uniform sensitivity was achieved.

Microphones

The instruments discussed so far operate without the benefit of electric-current amplifiers. The important role that these amplifiers

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[17] *Pogg. Ann.* **141**, 321 (1870).

[18] Debye and Sears, *Proc. Nat. Acad. Sci.* **18**, 409 (1932). Lucas and Biquard, *Jour. de Physique et le Radium* **3**, 464 (1932).

[19] R. Baer and E. Meyer, *Phys. Zeits.* **34**, 393 (1935).

[20] *Science of Musical Sounds*, The Macmillan Company (1922).

have played in recent developments of acoustic instruments has already been indicated. To apply such amplifying means we must first of all have a device to convert sound power into electrical power. By far the most important instrument of this class is the microphone, which is a device that translates sound into corresponding electrical currents. When a medium is traversed by a sound wave it undergoes periodic variations in pressure, density, temperature and particle velocity. A device which translates any one of these variations into corresponding electrical currents may be classified as a microphone.

The great utility of the carbon microphone rests upon the fact that it in itself functions as an amplifier, i.e., the electrical power generated is greater than that absorbed from the actuating sound wave. The carbon microphone, however, has not been widely used for acoustic measurements, lacking the requisite stability and constancy. After amplifiers became available high sensitivity was no longer so important. It became possible to develop microphones in which high sensitivity was a subordinate property but which were stable and constant and relatively free from distortion.

The sensitivity of a microphone as a function of the frequency can usually not be easily determined from its physical constants. It must, therefore, be calibrated to be useful for general acoustic measurements. Such calibrations are commonly made in terms either of the voltage generated per unit of pressure acting on the instrument, or of the voltage per unit of the pressure obtaining in a plane progressive sound wave before the microphone is placed in the sound field. The former is referred to as a pressure and the latter as a free field calibration. Very complete discussions of the various methods of effecting such calibrations have been given by L. J. Sivian [21] and by S. Ballantine.[22] Unless the dimensions are small compared with the wave-length the microphone will diffract the sound waves and the pressure on the diaphragm will not be the same as that of the undisturbed sound field; for example, at normal incidence and at frequencies for which the wave-length is small compared with the diameter of the microphone the pressure will be doubled. The diffraction effect exhibits itself, particularly in a variation in the response-frequency characteristic with angle of incidence of the sound wave, generally in not an easily predetermined manner. If the form of the instrument is that of a sphere it is possible to determine this variation with angle of incidence theoretically. Ballantine [23] and also Oliver [24] have, there-

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[21] *Bell Sys. Tech. Jour.* **X**, 96 (1931).

[22] *Jour. Acous. Soc. Amer.* **3**, 329 (1932).

[23] *Phys. Rev.* **32**, 988 (1928).

[24] *Jour. Sci. Inst.* **7**, 113 (1930).

fore, worked with instruments of this form. In any type of microphone diffraction effects can be entirely eliminated only by making the dimensions small compared with the wave-length.

The calibration of a microphone for a particular sound field may be carried out by measuring the undisturbed field with a device which is small compared with the wave-length and then noting the response of the instrument when placed in this field. This kind of calibration, when made in a nearly plane progressive wave, is referred to as a free field calibration. For the standard measuring instrument a Rayleigh disc is commonly used. This calibration is then applicable only for cases where we have substantially this type of sound field, i.e., when the microphone is at some distance from the source and all the sound is received by direct transmission. Where this condition is not fulfilled, the free field calibration is no true indication of the performance; for instance, when an instrument is used as a close talking microphone our experience indicates that in some cases at least an instrument having a flat characteristic, as obtained by a pressure calibration, delivers a voltage having frequency components of more nearly the same relative intensity as that in the voice when no microphone is near the mouth than does a microphone having a flat characteristic as given by a free field calibration. To eliminate diffraction effects a number of investigators have constructed microphones of small size, to some of which reference will be made in subsequent sections. Where it is necessary to make measurements with an extremely small instrument, such as in the exploration of the sound field within conduits and horns, the most satisfactory method of procedure is to use a small tube leading to a chamber closed over the diaphragm of a larger microphone.[25] The disadvantage of this arrangement is the fact that the loss in pressure through such tubes increases rapidly with frequency, so that at high frequencies it is necessary to work with high sound intensities or use uncomfortably high gain amplifiers. In working with single frequencies a great advantage in ease of measurement can be gained by the use of band-pass filters.

Pressure Microphones

Although microphones may conceivably be designed to translate directly the periodic variations of pressure, temperature, density, or particle velocity of a sound wave into corresponding electrical voltages, it is convenient to divide them into two classes: pressure microphones and velocity microphones, since the first three of the above characteristics of sound waves are proportional in any type of sound field.

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[25] Sell, *Wiss. Ver. d. Siemens-Konz.* **2**, 353 (1922).

Condenser Microphone

One of the first so-called high-quality microphones developed for use with amplifiers was of the condenser type. This is in principle one of the simplest of all microphones. It consists essentially only of two parallel insulated plates, one of them fixed and the other movable under the action of the alternating pressure of the sound wave. When these plates are connected in series with a resistance and a battery an alternating current will flow in this circuit in accordance with the variations in capacitance between the two plates. The resulting potential variations across the resistance are impressed on the grid of a vacuum tube.

A different method of using the condenser microphone has been described by Riegger.[26] The microphone is made a part of the capacitance element of a high-frequency electric oscillator. The frequency of the oscillations is thus modulated in accordance with the sound pressure acting on the diaphragm. If the modulated current is transmitted through a circuit, the transmission of which varies linearly with the frequency, in series with a linear rectifier, the output current of the rectifier will correspond to the sound pressure.

The condenser microphone as commonly used is of a size such that at the higher acoustic frequencies it will distort the sound field. The pressure and free field calibrations begin to diverge from each other at about 1000 c.p.s. To eliminate this distorting effect a number of investigators [27] have developed miniature condenser microphones for laboratory use. Generally such instruments have been designed at a sacrifice in sensitivity and uniformity of response. The small size microphone developed by Harrison and Flanders, however, has a remarkably flat response frequency characteristic and a sensitivity comparable with that of the larger instrument. Still smaller condenser microphones have been constructed but at a sacrifice in sensitivity.

At this point it may be of interest to give an example which illustrates the great advantage that the vacuum tube amplifier has given us in the design of sound measuring instruments. With an amplifier having a uniform amplification from 50 to 10,000 cycles, it is possible to measure, under favorable conditions, voltages as low as 1 microvolt. The amplitude of motion of the diaphragm of a common form of condenser transmitter delivering this voltage is about 10^{-11} cm., or about 1/1000 of an Angstrom. This illustrates the extremely small amount of motion that has to be imparted to the moving element of the

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[26] *Wiss. Ver. Siemens-Konz.* **3**, 2, 67–100 (1924).

[27] K. Hall, *Jour. Acous. Scc. Amer.* **4**, 83 (1932). Harrison and Flanders, *Bell. Sys. Tech. Jour.* **XI**, 451 (1932).

measuring instrument. Not even with an optical interferometer could we hope to evaluate displacements so small.

Moving Coil Microphone

The condenser microphone has inherently a high electrical impedance, so high in fact that any attempt to connect the microphone to an amplifier by leads of appreciable length results in a loss of voltage. To avoid this loss an amplifier of at least one stage has generally been placed in close connection with the microphone. However, since the input impedance of a vacuum tube is also high, the microphone can be connected to it without the use of an impedance transformer, a distinct advantage at the time when transformers of good frequency characteristic were not available. During the last few years, through the development of new magnetic materials and advances in design, it has been possible to build transformers having a substantially uniform response over the whole acoustic frequency range. This development has made it possible to design microphones operating on electromagnetic principles, which have a good response-frequency characteristic and a greater sensitivity than the condenser microphone. They have an important advantage over the condenser microphone in that, because of their relatively low and constant impedance, they may be connected to the amplifier by a relatively long cable without appreciable loss. One such instrument [28] is shown diagrammatically in Fig. 1.

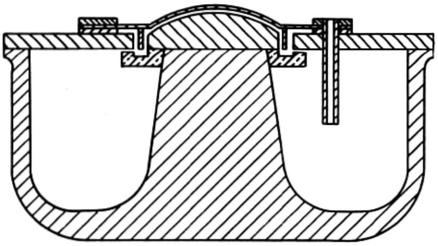

Fig. 1—Moving coil microphone.

The diaphragm has attached to it a coil which lies within a radial magnetic field. As the voltage generated by an axial motion of the coil is proportional to the velocity, if the same voltage is to be generated at all frequencies under a given sound pressure, the impedance of the moving element must be independent of frequency. This type of impedance characteristic over a wide frequency range is obtained by properly proportioned air chambers and resistances in back of the

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[28] *Jour. Acous. Soc. Amer.* **3**, 44 (1931).

diaphragm. This microphone, when provided with a coil having an electrical resistance of 20 ohms, will generate 10^{-4} volts per bar of sound pressure. The smallest voltage that can be measured at the terminals of a resistance is limited by the voltage due to thermal agitation of the electrons,[29] which under normal conditions and for a frequency band of 15,000 c.p.s. is equal to 7×10^{-8} volts for a resistance of 20 ohms. Hence the smallest pressure that it is possible to measure with this microphone is about 7×10^{-4} bars. However, over a narrow band of frequencies, or at a single frequency, measurements may be made down to still lower pressures if the circuit is provided with a band-pass filter. The sensitivity of this instrument is higher than that of any other microphone of comparable frequency range at present available. In evaluating some of the other microphone principles we shall, therefore, use its sensitivity as a reference, without meaning to imply that sensitivity is the sole criterion of the merit of a microphone. There is also an upper limit to the sound intensities that may be measured with this instrument. This is governed by the maximum amplitude of excursion that the diaphragm can make without the generation of appreciable harmonics. The upper and lower limits at the various frequencies are shown by the curves in Fig. 2.

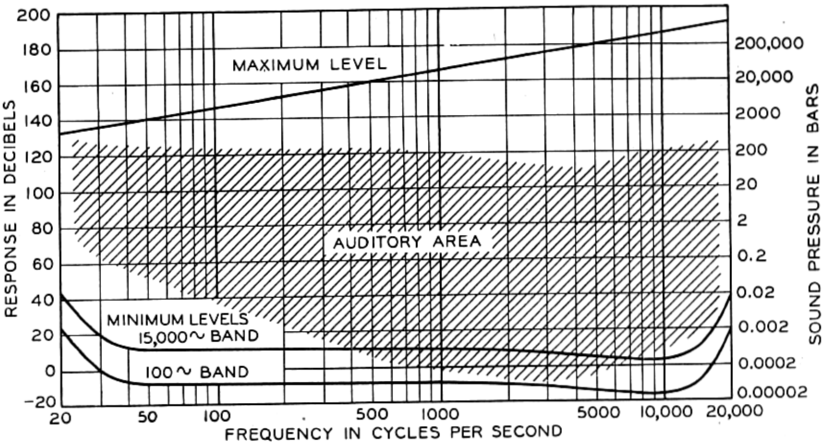

Fig. 2—Operating range of moving coil microphone.

The upper limit is taken as the pressure at which the higher harmonic components of the voltage are equal to 3 per cent of the fundamental. The lower limit represents the pressure at which the signal voltage is just equal to the voltage of thermal agitation. For comparison the

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[29] J. B. Johnson, *Phys. Rev.* **32**, 97 (1928).

corresponding auditory range is indicated by the cross-sectioned area. It will be noted that when operated at its full frequency range even this relatively sensitive microphone is incapable of translating practically sound of intensities as low as the ear can hear.

This instrument, which in a similar form is used as a commercial microphone, is several inches in diameter and so is not without effect on the sound field. Where a certain amount of operating range and sensitivity may be sacrificed, as in many acoustic measurements, it is possible to construct this instrument in a much smaller form.

Capillary and Magnetostriction Microphones

Besides the electrostatic and electromagnetic methods of translating the mechanical pressures of a sound wave into corresponding electrical potentials, there are other electromechanical phenomena which may be applied for the purpose. Outstanding among these are the capillary electrometer, magnetostriction, and piezoelectric action.

When a potential is applied at the interface between an electrolyte and mercury the surface tension is changed. If the mercury is in a capillary tube the change in surface tension will result in a change in position of the mercury; conversely when a force tending to move the surface is applied, there will be a resulting change in potential across the interface. This phenomenon has been applied in the design of microphones. One form of construction of such an instrument is shown in Fig. 3, taken from a paper by Latour.[30] The instrument appears to have been used but little up to the present time and there seems to be very little in the literature regarding its performance.

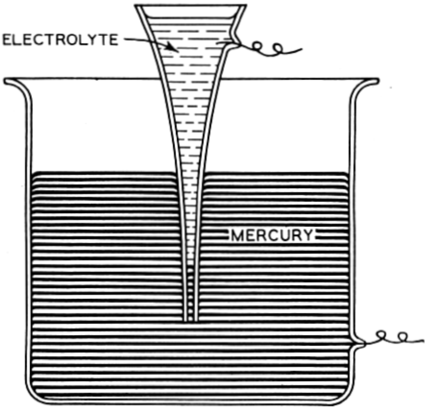

Fig. 3—Latour capillary microphone.

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[30] *Compt. Rend.* **186**, 223 (1928).

Magnetostriction also has found little application in microphones for air-borne waves at audio frequencies, although this principle has been applied with notable success in both the generation and detection of ultra-audio waves by G. W. Pierce and in the generation of audio frequency waves of high intensity in liquids.[31]

Piezoelectric Microphones

The application of piezoelectric action in the construction of acoustic microphones was first made by A. M. Nicolson,[32] who used Rochelle salt as the active material. Rochelle salt is unique in that its piezoelectric constant is about a thousand times as great as that of any other crystal. It has, however, several characteristics which would appear to render it unsuitable for use as a measuring microphone. It is mechanically fragile and its piezoelectric activity, under normal conditions, varies greatly with temperature, falling to a very low value for temperatures above 23° C. R. D. Schulwas-Sorokin [33] found, however, that by the application of a static stress the temperature coefficient could under certain conditions be greatly reduced and the activity extended to higher temperatures. C. B. Sawyer [34] found that if two thin slabs are cut and cemented together in such a way that one of the slabs will expand and the other contract when a potential is applied between the interface and the two outer surfaces, variations of activity with temperature are reduced to a low value. Presumably stresses are set up in the slabs by temperature variations which reduce the temperature coefficient of activity in accordance with the experiments of R. D. Schulwas-Sorokin. Sawyer has utilized these so-called bimorphic slabs in the construction of microphones. Single elements can be constructed of sufficiently small dimensions to avoid diffraction of the sound. In order to obtain microphones of greater practical efficiency a number of elements may be used in combination. If these elements are mounted symmetrically the translating efficiency will be the same in all directions about the axis of symmetry, as is the case for any microphone having an axis of symmetry. The amount of variation in respect to other directions depends upon the relation between the dimensions and the wave-length. According to the published data the sensitivity of a multiple element microphone of this type is about 25 db below that of a moving coil instrument.[35]

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[31] Gaines, *Physics* **3**, 209 (1932).

[32] *Trans. A. I. E. E.* **38**, 1315 (1919).

[33] *Zs. f. Physik* **73**, 9–10, 700 (1932).

[34] *Proc. I. R. E.* **19**, 2020 (1931).

[35] A. L. Williams, *Jour. S. M. P. E.* **23**, 196 (1934).

Of the more common piezoelectric crystals tourmaline possesses a characteristic which renders it peculiarly suitable for the absolute measurement of sound intensities at all audio frequencies, in that it may be so cut into slabs that a potential difference will be developed between its lateral surfaces when it is subjected to a purely hydrostatic pressure. Because of this characteristic Sir J. J. Thomson[36] suggested its use for measuring pressures in gun barrels. Such a slab of tourmaline, having dimensions small compared with the wavelength, except for its low sensitivity, is the ideal microphone. Tourmaline is mechanically strong and its activity is practically constant under all atmospheric conditions. Resonant frequencies in the slab lie far out of the range of audio frequencies so that the response at all frequencies is the same and is easily determined from static or low-frequency measurements. Unfortunately the sensitivity of such a device is low, some 70 db below that of a moving coil microphone. In spite of this low sensitivity it can be used for calibrating other microphones if sound waves of rather high intensities are used and if the electrical circuit is provided with a band-pass element transmitting only frequencies in the immediate neighborhood of the measuring frequency. A measuring system of this character, unlike the Rayleigh disc, is not subject to disturbances from circulating air currents.

Thermometric Microphones

As the pressure variations in a sound wave are accompanied by corresponding variations in temperature, corresponding electrical currents will be generated by a resistance thermometer or a thermocouple when placed in the sound field. The temperature variations are of the order of 0.0001° C. per bar acoustic pressure. The use of a resistance thermometer (for measuring these periodic temperature variations) was first investigated by Heindlhofer,[37] and more recently by Friese and Waetzmann,[38] who found that at a frequency of 1000 c.p.s. a wire 0.0004 cm. in diameter will undergo temperature variations equal to about 0.15 of the variations in the surrounding medium. To derive an alternating electric current from the periodic resistance variations that follow the temperature variations, a direct current must be passed through the wire. The heat generated by this current, unless it is kept down to an extremely small value, will set up convection currents around the wire and so greatly complicate the operation.

The thermocouple is entirely free from this objection, but is not readily constructed so as to have a heat capacity as small as the Wollas-

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[36] *Engineering* **107**, 543 (1919).

[37] *Ann. d. Physik* **37**, 247 (1912); **45**, 259 (1914).

[38] *Zs. f. Physik* **29**, 110 (1925); **31**, 50 (1925); **34**, 131 (1925).

ton wire. Recently A. E. Johnson [39] has been able to make thermocouples with exceedingly small heat capacities with which measurements have been made up to 5,000 cycles and it is stated that they are usable up to several hundred thousand cycles. They are so small that they do not alter the sound field by diffraction and are free from resonance effects inherent in most instruments depending upon mechanical movement. As compared with other types, thermocouple microphones have a low sensitivity, at least 100 db below that of the moving coil microphone, according to the data given by Johnson.

Velocity Microphones

All the preceding types of microphones depend ultimately for their operation upon pressure variations in the sound wave. As the two primary characteristics of sound are pressure variations and alternating flow of the air particles, it is possible also to design microphones which generate voltages in accordance with the velocity of the air particles.

Hot Wire Microphone

One form of microphone of this character depends upon the change in resistance of a heated fine wire resulting from changes in temperature produced by the transverse flow of air. A microphone operating on this principle was first devised by Tucker [40] and used extensively during the war for locating enemy artillery. In order to increase the sensitivity and reduce distortion a steady stream of gas should be passed across the wire. An application of this principle to the construction of a microphone is shown in Fig. 4. Maximum response is

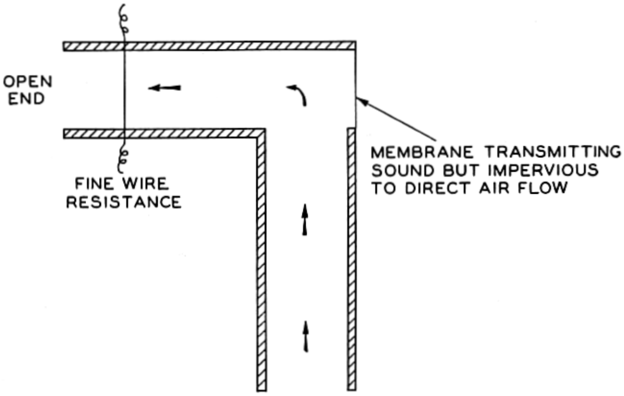

Fig. 4—Hot wire velocity microphone.

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[39] *Phys. Rev.* **45**, 645 (1934).
[40] *Phil. Trans.* **221**, 389 (1921).

obtained when the direction of the sound wave coincides with the direction of the steady stream. At a given frequency the resistance variation is nearly proportional to the product of the steady stream velocity, the particle velocity of the sound wave and the cosine of the included angle. Since velocity in contrast with pressure is a vector quantity, a velocity microphone will respond selectively to sound coming from certain directions even at low frequencies. This characteristic is of considerable advantage in certain types of measurements, for it is often possible to so place and orient the instrument that its response is a minimum for an interfering or disturbing sound and a maximum for the sound to be measured. An illustration of such an application in sound measurement or pick-up is shown in Fig. 5 where the instrument is so placed that it will receive the sound directly from the source, but is insensitive to the sound reflected from the floor or neighboring wall. Other examples of acoustic measurements, where benefit is derived from the directional characteristics of the velocity microphone, are discussed in a recent paper by Wolff and Massa.[41]

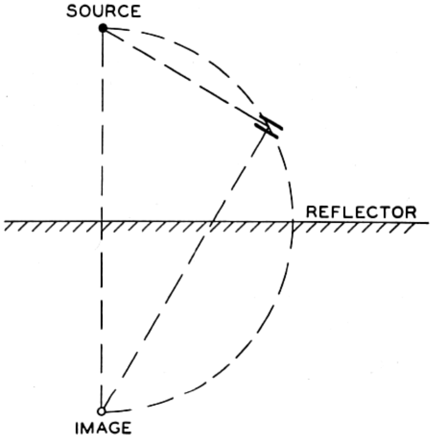

Fig. 5—Method of reducing effect of interfering waves with velocity microphone.

There is one other important difference in the performance of velocity and pressure microphones. In a plane progressive wave particle velocity and pressure are strictly proportional at all frequencies. For a spherical sound wave, the radius of curvature of which is small compared with a wave-length, this is no longer true.

[41] *Jour. Acous. Soc. Amer.* **IV**, 217 (1933).

If we have a simple source of constant strength $A \cos kct$, the pressure at a distance r is given by

$$\frac{A\rho f}{2r} \sin k(ct - r),$$

where ρ is the density, c the velocity of sound, and k is equal to ω/c. The particle velocity is given by

$$\frac{Af}{2cr}\left[1 + \left(\frac{\lambda}{2\pi r}\right)^2\right]^{1/2} \sin\left[k(ct - r) + \psi\right],$$

where ψ is a function of λ and r. It will be seen that the pressure varies inversely with the distance for all frequencies, while the relationship between velocity and distance involves the wave-length, or frequency. In Fig. 6 are given some response-frequency characteristics for several distances from the source of a velocity microphone having a uniform characteristic for plane waves. The change in characteristic as the instrument is brought close to the source is very marked. Some care is therefore required in interpreting the results of measurements made with this type of instrument. On the other hand, a pressure microphone, except in so far as diffraction may modify the sound field, will exhibit the same form of response-frequency characteristic at all distances from the source, so the wave form of the voltage generated by a pressure microphone will be the same for all positions in the free sound field of a simple source. This difference in characteristics of the two types of instruments is easily observed by comparing reproduced speech when the microphones are first placed near and then at some distance from the speaker's mouth.

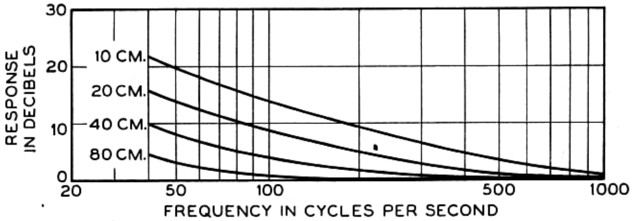

Fig. 6—Response of velocity microphone as a function of distance from source.

Ribbon Microphone

A form of microphone, which has been extensively used in recent years, is the ribbon microphone. Essentially it consists of a very thin strip of aluminum with circuit terminals at its two ends. This ribbon is placed in a magnetic field so that the lines of force lie in the plane of the ribbon and perpendicular to its long dimension, as shown in Fig. 7. Motion of the ribbon set up by sound waves will then generate a potential between its terminals. This type of microphone construction was first suggested by Reinganum.[42] It was developed into a practical form by Gerlach [43] and Schottky.[44] They apparently preferred to shield one side of the ribbon so that the instrument operated as a pressure microphone. H. F. Olson,[45] recognized the greater simplicity of the instrument in construction and in operation if both sides of the ribbon were freely exposed to the air. Constructed in this way the instrument is virtually a velocity microphone at least at low frequencies. At the higher frequencies the ribbon with its surrounding structure almost completely shields the rear from sound reaching the front of the ribbon at perpendicular incidence. Under these conditions the instrument operates substantially as a pressure microphone, but even at these frequencies sound reaching the instrument from a direction parallel to the plane of the ribbon is without effect. Curves published by Olson on the directional characteristics of this microphone show that in a plane perpendicular to the axis of the ribbon the variation of response with direction follows approximately a cosine law, where the angle is measured from a line drawn normal to the plane of the ribbon. The relationship is more complicated over a plane passing through the axis of the ribbon.

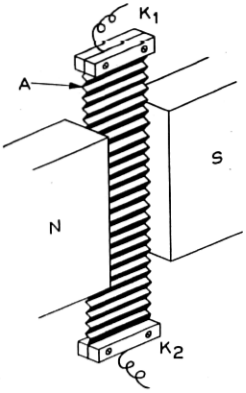

Fig. 7—Ribbon microphone.

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[42] *Phys. Zs.* **11**, 460 (1910).
[43] *Phys. Zs.* **25**, 675 (1924); *Wiss. Ver. Siemens-Konz* **3**, 139 (1923).
[44] *Phys. Zs.* **25**, 672 (1924).
[45] *Jour. Acous. Soc. Amer.* **3**, 56 (1931).

A microphone that responds to the velocity of the air particles has equal sensitivity for sound waves traveling in opposite directions. Weinberger, Olson and Massa [46] have modified the ribbon microphone so that its response is not the same for the positive as for the negative direction of propagation of the sound wave. So modified the microphone has a greater response for sound waves coming towards one side of the ribbon than for those coming towards the other side. In a plane wave the magnitude of the pressure and the velocity are proportional. For waves traveling in a positive direction the two are in phase and for waves traveling in the negative direction they are in opposite phase. If, then, a pressure and a velocity microphone of equal sensitivity are connected in series the resultant voltage will be double for sound of normal incidence coming from one direction and equal to zero for sound coming from the opposite direction. Weinberger, Olson and Massa placed an appropriate acoustic impedance over a part of the ribbon so as to give this part the characteristics of a pressure microphone, while the other part of the ribbon was left free so as to function as a velocity microphone. The voltage at the ends of the ribbon is then proportional to the vector sum of the pressure and the velocity in the sound wave. In this way a pressure and velocity microphone combination is obtained in one instrument. It is insensitive to sound falling at perpendicular incidence on one side of the ribbon but not to sound propagated in the plane of the ribbon, as in the case of a velocity ribbon microphone.

ELECTRICAL INSTRUMENTS OF PARTICULAR INTEREST IN ACOUSTICAL STUDIES

So far our discussion has been restricted mainly to microphones and instruments used in their calibration. There have, of course, in recent years been developed many other devices especially adapted for the quantitative study of particular acoustic problems, but a rather extensive discussion of the microphone has been given because it is an adjunct in almost all of these other instruments. In great part acoustic measurements are today made by first translating sound into a corresponding amplified electric current. The results of measurement or analysis of this current may then be referred back to the sound if the characteristics of the translating device are known. The type of analyzer or measuring instrument applied to the electrical circuit depends then altogether upon the kind of information that is desired. Strictly speaking we should classify these not as acoustical but as electrical instruments. In fact, every kind of electrical instru-

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[46] *Jour. Acous. Soc. Amer.* **5**, 139 (1934).

ment may at times find an application in the study of acoustical problems. We must, therefore, necessarily restrict ourselves to a discussion of the kind of instruments which can give types of information of general acoustical interest.

The Oscillograph

If we wish to obtain a complete picture of the sound wave the microphone amplifier output is connected to an oscillograph, which is a device for translating a time pattern of the electric current into a corresponding space pattern. If an undistorted pattern is to be obtained, not only must the various harmonic components of the current and the recorded wave have the same relative amplitudes, but their phase relationships must be preserved. One form of instrument very closely satisfying these conditions up to about 10,000 cycles is a Curtis string oscillograph,[47] which is a modified form of the Einthoven galvanometer. The arrangement of this instrument is shown diagrammatically in Fig. 8. It records the wave form optically on photographic paper, which is automatically developed and fixed within a fraction of a minute after exposure.

In certain types of problems one of the various recording devices employed in the production of sound pictures may be used advantageously. These instruments have, in general, not been designed to be free from phase distortion but the records are in a form suitable for reproduction so they lend themselves particularly to the study of the subjective aspects of sound.

When the sound wave to be studied is steady, the wave form can be conveniently observed or photographed by means of a cathode ray oscillograph. These instruments are now to be had in convenient form. When used with an automatic sweep circuit, as suggested by Bedell and Reich,[48] the wave form of any steady state current is shown as a stationary pattern on a screen. These oscillographs are generally free from both frequency and phase distortion up to the highest audio frequencies.

Harmonic Analyzers for Steady Currents

If we wish to study the composition of a sound wave in terms of its harmonic components we may, of course, analyze the oscillographic records by means of any one of the well known methods of harmonic analysis, but this is at best a laborious process. Also, it is usually difficult to read an oscillogram with sufficient accuracy to determine the magnitude of any component that is much smaller than that of the

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[47] *Bell Sys. Tech. Jour.* **XII**, p. 76.

[48] *Science* **63**, 619 (1926).

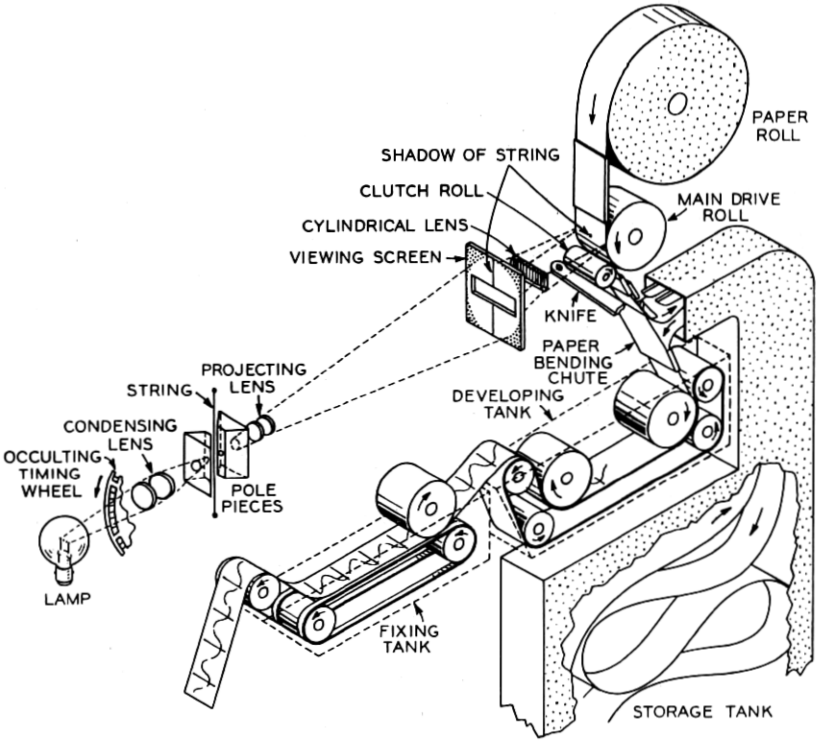

Fig. 8—Diagrammatic arrangement of Curtis oscillograph.

maximum component. When the conditions are such that a current can be steadily maintained, the analysis can be made much more conveniently and generally over a wider range of amplitudes by means of one of a number of recently developed types of current analyzers. These analyzers, although the mode of operation may differ in the various types that are available, have the common characteristic that they transmit only a narrow band of frequencies with the position of the band adjustable along the frequency scale. For analyzing a current wave the mid-frequency of the transmission band is shifted along the whole frequency range and the magnitude of the current in each frequency region is recorded or noted on a meter. This type of analyzer may also be used to get a statistical distribution of the power with respect to frequency when the sound is not periodic, as in certain kinds of noise.

High-Speed Analyzers

For the rather detailed study of sounds whose wave form varies with time, such as those of music or speech, an instrument is needed which shall indicate the variations with time in the frequencies and amplitudes of all the harmonic components. Analyzers of the type just described indicate at a given instant the amplitude of only one component. In order to follow variations in all the components it would be necessary to sweep the frequency of transmission of the analyzing circuits rapidly back and forth over the frequency range of interest. The selective element of the analyzer, however, possesses a finite time constant; that is, when the selective circuit is set at a given transmission frequency a finite time is required for the transmitted current to reach a certain fraction of its steady state value and, similarly, a finite time is required for the current to decay to a certain fraction of this value when the transmission frequency is changed. This time constant depends to some extent upon the shape of the transmission versus frequency characteristic of the analyzing circuit but, in general, it bears an inverse relation to the selectivity. It is therefore not possible with an analyzer of this type, having a single variable selective element, to perform a rapid analysis without sacrificing resolution. This difficulty can, however, be circumvented if the analyzer is provided with a large number of fixed selective elements which are continuously operative. To build up the large number of required circuits from electrical elements would be extremely costly and would result in a bulky piece of apparatus. A compact form of analyzer having a large number of fixed selective mechanical elements has recently been described by C. N. Hickman.[49] This device has a series of tuned reeds, all driven electromagnetically at the same time by the current to be analyzed. The reeds are tuned so that their resonant frequencies differ progressively by equal pitch intervals. One hundred and twenty reeds are used to cover the range from 50 to 3,200 cycles. The deflection of each reed is made visible by the projection on a screen of a spot of light reflected from a mirror attached to the reed. The strength of each component in the current may thus be observed simultaneously on the screen or, if desired, the deflections may be recorded photographically.

A different and ingenious approach to this problem has been made by E. Meyer[50] in a recently described instrument. By methods well known in communications engineering the frequency of each component in the current to be analyzed is increased by an equal amount. A special high-frequency loud speaker translates the resultant currents into sound waves which are now all of very short wave-length. These waves are reflected from a concave grating made up of a large number

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[49] *Jour. Acous. Soc. Amer.* **6**, 108 (1934).

[50] *Zeits. für Tech. Phys.* **12**, 630 (1934).

of equally spaced rods. The component waves are brought to a focus at different points along a focal surface analogous to the dispersion of light waves by an optical grating. A high-frequency microphone is moved back and forth along the focal plane through an amplitude large enough to cover one order of the spectra. This microphone is connected to an appropriate meter which records optically the intensity at various parts of the spectrum, which have a 1:1 correspondence with the component frequencies in the original current.

Measurement of Pitch

For acoustical studies, where it is of no particular importance to know the wave form but where interest lies in the variation of pitch with time, as in the study of the vibrato in musical tones, or in the inflections of the speaking voice, several types of instruments have been devised. Perhaps of these the most widely known is the tonoscope developed by C. E. Seashore [51] and his associates, which operates on the stroboscopic principle. This instrument has rows of uniformly spaced dots on a rotating cylinder, the number of dots increasing in successive rows. A neon light is made to flicker in synchronism with the fundamental of the tone under investigation. The particular row which under the light appears stationary gives the pitch of the tone at any instant. By the aid of a suitable camera the time variations of pitch may be recorded photographically, giving a so-called strobophotograph.

A frequency recorder operating on a different principle has been described by Hunt.[52] By a special circuit arrangement, employing gas-filled discharge tubes in combination with a spark recorder, the pitch of a tone can be recorded on paper. The scale is linear up to 8,000 cycles. This instrument is capable of following changes in pitch at a high rate of speed.

High-Speed Level Recorder

In some important types of sound measurements we are not interested in a detailed analysis of the sound wave but merely in the variation with time of the average level of the sound, as in the measurement of the rate of decay in a room or the flow of energy in speech, music, or noise. In some cases this average is preferably taken over long and in others over short time intervals. For long time averages, a thermocouple or rectifier and an ammeter may be used, but for short time averages an instrument is required which can follow changes in intensity at a higher rate of speed. Frequently also the range of inten-

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[51] *Jour. Acous. Soc. Amer.* **2**, 77 (1930).
[52] *Rev. Sci. Inst.* **6**, 43 (1935).

sities over which we desire to make measurements of this character is very wide. Reverberation measurements are preferably made over a range of at least 60 db and the level range of orchestral music covers about 75 db. Several instruments designed for such purposes have been described recently.[53] In the instrument described by Wente, Bedell and Swartzel the level is recorded by a stylus on waxed paper. The recorder can be adjusted to give either a short or a long time average. At the higher speeds it is capable of following changes in intensity at the rate of 840 db per second and fluctuations in intensity of about 100 per second. The instrument may be adjusted so that the full scale covers a range of 30, 60 or 90 db.

LOUDNESS MEASUREMENTS

The preceding discussion was restricted to the purely objective or physical aspects of sound. In certain types of acoustical problems, as in the study of noise, we are, however, interested in subjective characteristics, but we do not yet have instruments which respond to an acoustic stimulus in the way the brain does through the ear. In fact

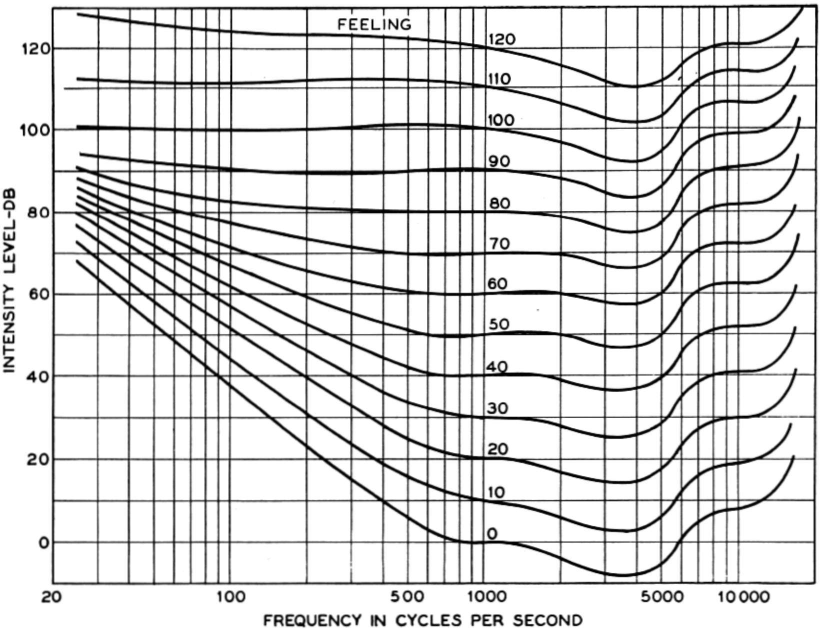

Fig. 9—Auditory chart.

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[53] Hunt, *Jour. Acous. Soc. Amer.* **6**, 54 (1934). Wente, Bedell and Swartzel, *Jour. Acous. Soc. Amer.*, January, 1935.

we are not yet completely clear as to the relationship between sensation and stimulus, although Fletcher and Munson[54] have developed formulae whereby the loudness level of a steady sound can in most cases be computed from the intensity level of its components. For single pure tones the relationship between sensation and stimulus has been extensively explored with the results which are indicated in the auditory chart shown in Fig. 9, as given by Fletcher and Munson. The various curves give the intensity level of pure tones of equal loudness. This chart gives some idea of the complexity of the relationship between loudness and stimulus. The threshold of audibility of course varies widely with frequency and the relationship between sensation level and intensity level is not the same at the various frequencies and levels; for instance, at a loudness level of 40 db above threshold, a change of 5 db in the stimulus at 100 cycles produces the same change in sensation as a change of 10 db at 1,000 cycles. Fechner's law does not hold strictly over a wide range of intensities at any of the audible frequencies. The difficulty of devising an instrument which would have similar characteristics is apparent. "Sound level meters" have, however, been designed which give a reading which is approximately proportional to the subjective intensity of the sound. These meters are generally so designed that they have a frequency characteristic corresponding to the auditory curve at about the level of the noise being measured. They have proved themselves extremely useful although from our knowledge of hearing phenomena we might expect large variations in the actual loudness of sounds of different character, even if a noise meter of the above type should show them to be equal.

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[54] *Jour. Acous. Soc. Am.* **5**, 82 (1933).