XI. *A Selective Hot-Wire Microphone.*

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Contents.

§ 1. *Introduction.*

The instrument described in the following paper provides :—

(i) A convenient means of detecting a note of given pitch when other sounds are present ; and

(ii) A method of estimating the relative intensities of sounds of the same pitch.

The idea which formed the starting-point for the construction of the instrument—viz., the placing of an electrically heated grid of fine platinum wire in the orifice of an otherwise closed vessel—was originally employed by one of us (W. S. T.) in the construction of a sound-detector for the use of Sound Ranging Sections in the British Army.* In its original form, the detector was intended to respond to heavily damped aerial vibrations, such as those produced by the firing of guns. Further experiments, however, showed that the detector could be tuned to respond to any continuous sound of definite frequency by suitably choosing the dimensions of the vessel and its orifice.

The tuned instrument is highly selective in its action. It is very sensitive when used to detect low-pitched sounds, but its sensitivity is diminished for the higher

* British Patent No. 13123 of 1916, and No. 8948 of 1918 ; United States Patent No. 269902 of 1919.

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pitches. The highest note with which we have experimented hitherto was one of 512 vibrations per second.

During the course of a large number of experiments with various types of sound-collectors and transmitters, we have found this selective form of hot-wire microphone to be of great assistance. It is very simply constructed and easily manipulated, and for many purposes the only electrical circuit needed is a Wheatstone's Bridge. If, however, it is desired to use aural methods, or if the sound to be observed is exceedingly faint, it is necessary to amplify (by means of thermionic valves) the electrical effects occurring in the microphone. When amplification is used it is possible to detect and render audible a pure tone which is quite inaudible to the unaided ear.

This form of microphone provides us with a very convenient instrument for comparing the efficiencies of various forms of sound-collector—particularly when these are considered in relation to the wave-length of the sound employed. It can also be used for determining the distribution of intensity at the focus of an acoustical lens or mirror, and (what is very important in many practical problems) the manner in which sound is diffracted by obstacles of various shapes and sizes. In addition to these and similar experiments, the microphone can be employed to estimate the relative strengths of the harmonics in an impure sound such as that produced by the usual form of Seebeck's siren. Some examples of these applications of the microphone will be given in the last section of this paper.

So far as we are aware, there is no other instrument of a selective character which could be used for making observations of the kind indicated above. In nearly all cases where attempts have been made to measure or analyse sounds, the instruments employed have depended on the setting in vibration of some form of diaphragm. Such instruments are generally insensitive to notes of moderately low pitch, and are, moreover, easily disturbed by vibrations communicated through the mounting of the diaphragm. For this reason methods of amplification are often of little service if the mountings are to be moved during the experiment.

The hot-wire instrument here described seeks to avoid this disadvantage by measuring directly vibrations which are set up in the air itself, but the displacements in progressive waves are so extremely small that they have been increased by resonance. This employment of resonance naturally limits the scope of the microphone (so that it cannot, for example, be employed for telephony), but it has the advantage not only of magnifying the sound to be recorded, but also of isolating from a complex sound the particular tone which it is desired to measure.

The closed vessel with a single orifice (in which the platinum wire grid is mounted) forms the well-known Helmholtz resonator. The advantages possessed by this form of resonator are :—

(1) That the resonance is sharp.
(2) That the overtones are all relatively high.

(3) That the overtones are not in harmonic relation ; and

(4) That the dimensions of the resonator need only be small compared with the wave-length of the sound to be observed.

The simplified theory of such resonators is due to RAYLEIGH,* who showed that the number of vibrations in the resonant note is given by

$$N = \frac{V}{2\pi}\sqrt{\frac{c}{S}},$$

where V is the velocity of sound in the gas in the neck, S is the volume of the reservoir, and c is a quantity depending on the shape and dimensions of the orifice and called (from an electrical analogy) the "conductivity" of the orifice.

§ 2. *Description of the Microphone.*

The complete microphone, comprising the Helmholtz resonator with the platinum wire grid suitably mounted in the neck, is made for convenience in three separate parts :—

(i) The platinum wire grid, mounted in a circular mica plate.

(ii) The "holder," which includes the neck of the resonator and the necessary contact-pieces and terminals for carrying current to the grid ; and

(iii) The "container," or reservoir.

A short description of each of these three parts will now be given.

(i) *The Platinum Wire Grid.*—Fig. 1, A, shows one form of the grid. It consists of a circular plate of thin mica 4 cms. in diameter, in the centre of which is cut a circular hole 0·65 cm. in diameter. A number of small pin-holes are punched at the edge of

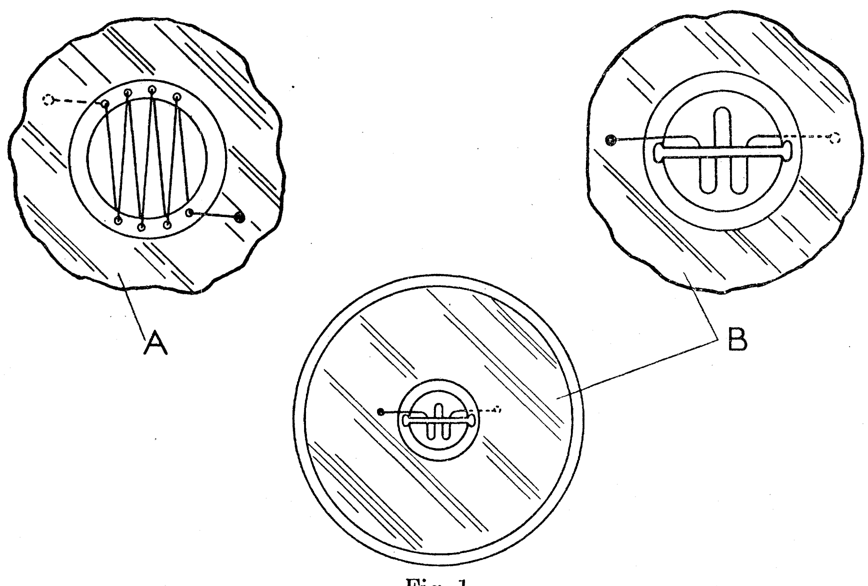

Fig. 1.

* RAYLEIGH, 'Theory of Sound,' vol. II., p. 174.

this circular opening, and through these the wire is threaded to form a zig-zag grid as shown in the figure. To each side of the mica plate is attached an annular plate of silver foil (shown by shaded portion in the figure), and to each of these plates is soldered one end of the platinum wire. The two plates of silver foil thus constitute the electrodes of the wire grid.

Fig. 1, B, shows another form of grid, for the design and manufacture of which we are indebted to the Research Department of the General Post Office. The wire is bent into three loops, and is supported by a small rod of glass-enamel placed diametrically across the opening in the mica plate.

The grids are made in the first place with Wollaston wire, the silver sheath being removed by means of nitric acid after the wire has been mounted in position. During this part of the process of manufacture the silver foil electrodes are protected by a coating of paraffin wax.

The grids used in the experiments described in this paper were, unless otherwise stated, of the type shown in fig. 1, B. The wire, the diameter of which was about 0·0006 cm., carried a maximum current of about 30 milliamperes, the exact amount varying in individual grids according to the sample of wire used in their manufacture. The average resistance at 10° C. was about 140 ohms, and about 350 ohms when carrying a safe working current of 25 to 28 milliamperes. In the case of a particular grid, it was found that its resistance was 125·5 ohms at 0° C., 133 ohms when carrying a current of 0·5 milliampere, 156·2 ohms at 100° C., and 332 ohms when carrying its working current of 32 milliamperes. The working current heats the grid to just below red heat.

For certain purposes grids were made from wire 0·0015 cm. in diameter and carrying a maximum current of about 55 milliamperes. The number of loops was increased in these grids to eight, four on each side of the glass-enamel support.

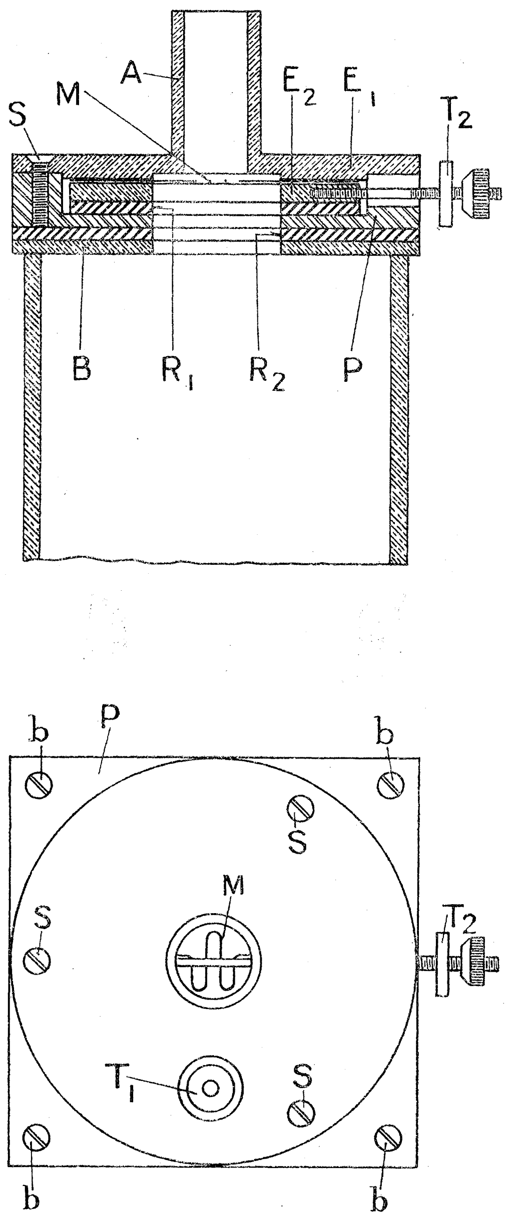

Fig. 2.

(ii) *The "Holder."*—The manner in which the holder is made up is shown in fig. 2. The cylindrical neck A, made of brass, is soldered into the centre of the circular plate

E_1 made of the same material. E_1 is provided with the terminal T_1. The mica plate (M) carrying the grid is clamped between E_1 and the lower ring E_2, which is also of brass and carries the terminal T_2 at the side of the holder. Beneath E_2 is a rubber ring R_1, and this rests on a bed of ebonite (P) to which also the plate E_1 is fixed by the screws S. The ebonite bed (P) is square, and is bolted at the corners to the square brass plate (B) which forms one end of the container. To ensure an air-tight joint a square plate of thin rubber R_2 is inserted between the holder and the container.

When the plate E_1 is screwed down on to the ebonite bed, so that the mica plate with its silver foil electrodes is firmly held between E_1 and E_2, a current can be passed through the grid by connecting a battery to the terminals T_1 and T_2.

The neck (A) forms the channel of communication between the interior of the container and the outside air, and from an acoustical point of view is the most important part of the holder. If the capacity of the container be given, it is on the hydrodynamical conductivity of this neck that the pitch of the resonator depends. The dimensions of the neck generally used were: length 2·2 cms., internal diameter 0·75 cm. In certain experiments, however, the neck was made rather shorter than this in order to tune the resonator to some given pitch.

When the grid is being placed in position between E_1 and E_2 it is important to see that the circular aperture in the mica plate is coaxial with the neck, since even a small displacement from this position will change the pitch of the resonator by an appreciable amount.

(iii) *The "Container."*—The containers were in most cases made from brass tubing. One end of the tubing is closed with a circular brass plate, while at the other end is fitted a square brass plate of the same dimensions as the base of the ebonite bed of the holder, which is bolted to it by means of the bolts *b*, as shown in fig. 2. A circular hole $\frac{1}{2}$-inch in diameter is cut in the middle of this square plate to allow a free passage of air through the neck into the container. The thickness of the brass of which the tubing was made was 1 mm.

The natural pitch of the resonator of course depends on the volume of the container. Thus, with the form of neck described above, a volume of 290 c.c. gives the resonator a pitch of 116 vibrations per second, while a volume of 68 c.c. gives it a pitch of 240 vibrations per second. For pitches below 200 vibrations per second it has been found convenient to use brass tubing from 2 to $2\frac{1}{2}$ inches in diameter, while for higher pitches (above 200) tubing about 1 inch in diameter is the most suitable.

Other forms of container have been made and tested, and reference to some of these will be found in a later paragraph. The material from which the container is made, and the thickness and rigidity of the walls, have a very marked effect on its resonating properties. The most efficient resonator which was tested was one which had been drilled out of a solid piece of brass, and its superiority must be attributed, in the main, to the increased strength of the walls.

For experimental purposes it is often desirable to have a microphone whose pitch can

be varied at will. This can easily be made by fitting a wooden plunger inside the brass tubing of the container, or by making the container in two parts of different sized tubing so that one part will slide over the other.

Another method of tuning the microphone is to alter the length of the neck. It is, however, inadvisable to reduce the length of the neck to less than 1 cm., as with shorter necks than this the grid is exposed to the effect of transient currents of air.

§ 3. *Electrical Connections.*

When the air in the neck of the resonator is set in vibration by a sound of suitable frequency, the platinum wire grid suffers a change in resistance, which may be regarded as being made up of an oscillatory change and a steady change. There are thus two ways in which the microphone can be used.

(i) *The Amplifier Method.*—If the oscillatory effect is to be observed it is necessary to include an amplifier in the circuit. A suitable form for the circuit to take is shown in fig. 3,

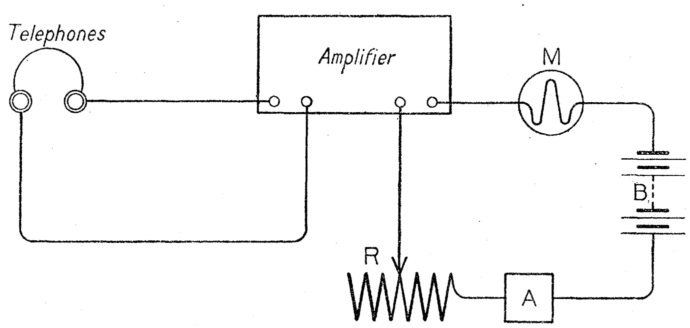

Fig. 3.

where the microphone (M) is connected in series with a battery (B), a milliammeter (A), a rheostat (R), and the primary of the input transformer of a three-valve amplifier.* The sound can of course be heard in the telephones, and provided that the grid lies in an approximately horizontal plane (*i.e.*, that the axis of the neck of the resonator is vertical) the pitch heard is the same as that of the original sound. The effects which occur when the grid is moved out of the horizontal plane are described in § 8 ; but it may be noted here that not only the pitch of the note heard in the telephones, but also the sensitivity of the microphone, depend on the inclination of the grid to the horizontal plane. It is therefore important in any experiment where comparisons of the strength of sound are being attempted, that the position of the microphone relatively to a horizontal plane should not be changed during the experiment. The difficulty can be overcome by arranging that the microphone shall always hang so that the axis of the neck is vertical. Small deviations of one or two degrees from this position do not materially affect the sensitivity.

* Several different types of amplifier have been tried for this purpose. The best results have been obtained with a four-valve resistance amplifier specially designed for low acoustic frequencies.

The grid carries, normally, a heating current of about 27 milliamperes. When the resonator responds to a sound, the to-and-fro motion of the air in the neck produces, as already stated, an oscillatory change of resistance, and the effect of this is to superimpose on the steady heating current a ripple of small amplitude (generally only a few microamperes). It is this ripple which is amplified and which is heard in the telephones.

It is shown in a later paragraph (§ 7) that the magnitude of the amplified current may be used as a means of estimating the amplitude of a sound. For this purpose the telephones are replaced by a vibration galvanometer tuned to the pitch of the sound.

This method of employing the microphone for the measurement of a sound, however, is not altogether satisfactory, on account of the difficulty of maintaining an amplifier in such a condition that the current amplification is constant for any length of time; and for this reason the Wheatstone's Bridge method is sometimes preferable. The advantages of the Amplifier Method are that it is very sensitive (especially when a vibration galvanometer is used) and that the microphone can be placed in a moving piece of apparatus, subject only to the restriction that its axis must always be vertical (or at some fixed angle to the horizontal). Vibrations communicated through the mounting of the microphone (even when they are produced by striking the container) have very little effect on the sound heard in the telephones.

(ii) *The Wheatstone's Bridge Method.*—This method is preferable to the Amplifier Method on account of its greater simplicity, and because there is no danger of the sensitivity changing during the course of a long series of observations. A convenient form for the Bridge to take is shown diagrammatically in fig. 4. The microphone (M)

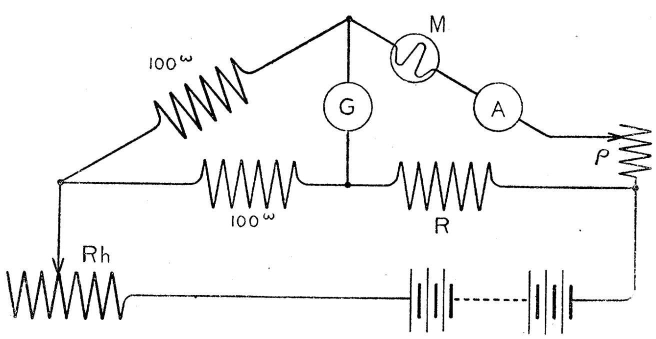

Fig. 4.

with the milliammeter (A) forms one arm of the Bridge. The balancing arm (R) is made about equal to the resistance of the grid when carrying its working current, *i.e.*, about 350 ohms. The rheostat (Rh) is inserted (as shown) in series with the battery, a balance being obtained by adjusting (Rh) until the current through the microphone brings its resistance (together with that of the milliammeter) up to R. For some purposes it is convenient to have a small variable resistance ρ in series with the microphone. In most experiments it is sufficient to take the deflection of the galvanometer as a measure of the intensity of the sound affecting the microphone; but other methods can of course

be used, such as measuring the increase of current required to bring the grid back to its initial resistance, or determining the alteration in resistance when the current is maintained at a constant value.

It is important when using the microphone in this way that it should not be moved during the course of an experiment. This is one of the disadvantages of the method. A small alteration in the tilt of the microphone upsets the balance of the Bridge and renders the sound-measurements inaccurate. If θ is the angle between the axis of the microphone and a vertical line (so that $\theta = 0$ when the microphone is held in its normal position with neck uppermost), then it is found that as θ is increased the resistance of the grid gradually falls and reaches a minimum when θ is about 100 degrees. The fall in resistance is then about 3 ohms (see fig. 13).

The resistance of the grid also changes when the microphone is rotated about its own axis, except of course when the axis is vertical. Thus, if the microphone is held in a horizontal position and in such a way that the glass-enamel support also lies horizontally, then a rotation of 90 degrees, bringing the glass-enamel support into a vertical position, is accompanied by a fall in the resistance of the grid of about 1 ohm.

All these effects are due to the influence of the convection currents issuing from the heated wire, and it appears that if the convection current from one part of the wire impinges on another part of the wire the resistance of the grid as a whole is always lowered.* As will be seen from the experiments described later, these convection currents play a very important part in the working of the microphone.

Although the resistance of the grid is changed (current being constant) when the plane in which it lies is altered, there is but little change in the sensitivity of the microphone, whether it is held horizontally or vertically, provided that its initial resistance is the same.

§ 4. *Sharpness of Tuning of the Microphone.*

The natural pitch of a microphone can best be determined by plotting its resonance curve. For this purpose the microphone to be tested is set up at a distance of two or three feet from a siren (a modified form of Seebeck's siren was used in the present experiments), and the grid is connected into one arm of a Wheatstone's Bridge as shown in fig. 4. The strength of the blast of air in the siren having been adjusted to a suitable value, a series of readings are taken of the deflection of the galvanometer and the pitch of the siren note. The curve formed by plotting deflection against the interval n/p ($n/2\pi$ being the resonant pitch of the microphone and $p/2\pi$ the pitch of the siren note) gives what we shall call the "resonance curve" of the microphone.

* The mutual action due to convection of two electrically heated fine platinum wires is described by J. S. G. THOMAS: "An Electrical Hot-Wire Inclinometer," 'Proc. Phys. Soc. Lond.', vol. XXXII, pp. 291–314 (1920).

A typical example of a curve obtained in this way is shown in fig. 5, the natural pitch of the microphone being 240 vibrations per second.

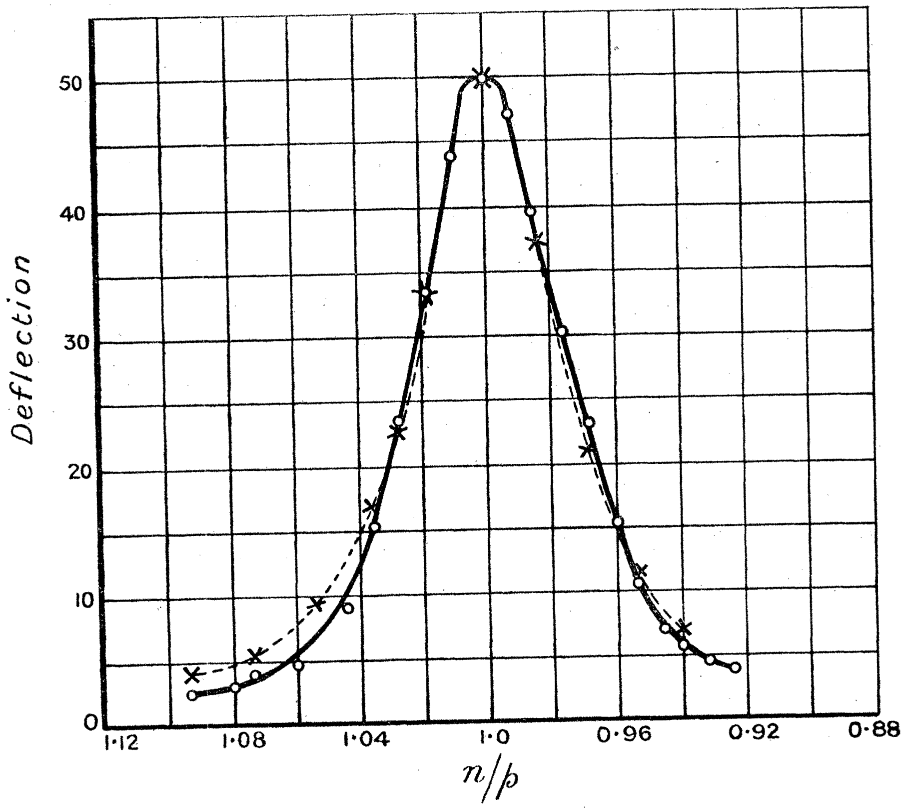

Fig. 5.

In order to obtain reliable resonance curves it was found necessary to make observations out of doors. When the experiments were performed indoors the results were in nearly all cases vitiated by the setting up of stationary waves in the room containing the apparatus.

Experiments are described in a later paragraph (§ 7) which show that—within limits—the change of resistance of the grid is proportional to the square of the amplitude (and therefore to the energy) of the vibration in the neck of the resonator, when the pitch of the stimulating sound remains constant. The influence of a change in the pitch of the sound upon the resistance change of the grid (apart from its effect on the response of the resonator) has not yet been investigated. In dealing with the resonance curves, where in any particular experiment we are concerned only with a comparatively narrow range of frequencies, we shall regard the deflection of the galvanometer as being proportional to the vibrational energy in the neck. Precautions were of course taken to ensure that the deflections were proportional to the changes in resistance suffered by the grid.

As stated above, the source of sound used in these experiments was a modified form of Seebeck's siren. It consisted of a heavy circular brass plate pierced with a ring of

twelve equidistant holes. This plate was rotated by an electric motor, the speed of which could be regulated by means of a rheostat in series with the armature. A stream of air, forced through a nozzle against the ring of holes, was supplied from a gas-compressor. The speed of the siren-plate was given by an Elliott speed-indicator attached to the motor, the readings of this instrument being proportional to the frequency of the fundamental note of the siren. The end of the nozzle and the holes in the siren-plate were so shaped that the area through which air could escape from the nozzle was proportional to $(1-\cos pt)$, $p/2\pi$ being the number of holes passing the end of the nozzle per second.* It was found by experiment (using a Hot-Wire Microphone) that with this arrangement the note produced by the siren was remarkably free from harmonics. It will be assumed in what follows that, within the limited range of frequencies over which a resonance curve is plotted, the amplitude of the sound produced by the siren remained sensibly constant.

On the understanding that the results may be subject to some revision on account of these assumptions, we can deduce the degree of damping of the Helmholtz resonator used to obtain the curve in fig. 5.

If the equation of motion of the forced vibration in the neck of the resonator is written

$$\frac{d^2x}{dt^2}+2\mathrm{K}\frac{dx}{dt}+n^2x=f\cos pt,$$

where $\frac{dx}{dt}$ is the instantaneous current of air in the neck, and $n^2 = \mathrm{V}^2c/\mathrm{S}$, then the forced vibration is

$$x=\frac{f}{\{(n^2-p^2)^2+4\mathrm{K}^2p^2\}^{\frac{1}{2}}}\cos(pt-\theta),$$

and the average energy of the vibration in the neck is proportional to the average value of $\left(\frac{dx}{dt}\right)^2$, that is, to

$$\frac{f^2}{n^2\left(\frac{n}{p}-\frac{p}{n}\right)^2+4\mathrm{K}^2}.$$

It is found that the experimental curves can be fairly well represented by an expression of this type, provided that a suitable value is given to K. Thus, by choosing $\mathrm{K} = 38 \cdot 5$, we obtain the dotted curve shown in fig. 5, which approximates closely enough to the experimental curve to show that this is about the proper value for the damping factor. In all cases so far examined the value of K required to fit the experimental curves has been found to lie between 20 and 40, and it has generally been found that K is less for the low-pitched resonators. For example, with a resonator whose natural pitch was 112 vibrations per second, the value of K was found to be 22·2.

* For the design of this siren-plate we are indebted to Messrs. R. H. Fowler and E. A. Milne, of Trinity College, Cambridge.

The forced vibrations of a resonator, due to an external source of sound, have been considered by RAYLEIGH (" Theory of Sound," vol. II., p. 195). If the periodic change of pressure at the mouth of the resonator is represented by Fe^{ipt}, the equation of motion applicable to the forced vibration in the neck is

$$\frac{d^2x}{dt^2}+\frac{p^2c}{2\pi V}\frac{dx}{dt}+n^2x=\frac{cF}{\rho}e^{ipt},$$

where c is the hydrodynamical conductivity of the neck and ρ is the density of the air. The term representing dissipation is here a function of frequency, but it represents " only the escape of energy from the vessel and its neighbourhood, and its diffusion in the surrounding medium, and not the transformation of ordinary energy into heat." It is found to be quite inadequate to account for the experimentally determined rate of dissipation. If $p/2\pi = 112$ vibrations per second, $c = 0\cdot 13$ cm. (determined experimentally), and $V = 33760$ cm. per second, then

$$\frac{p^2c}{4\pi V}=0\cdot 15,$$

which must be compared with the experimentally determined value of 22·2. It is clear, therefore, in the case of resonators such as those used in these experiments, that the dissipation is due in the main to other causes than the escape of energy through the neck, such as the effect of viscosity on the motion in the neck, and the lack of rigidity in the walls of the container. When we consider the obstructions caused by the glass-enamel rod supporting the grid and the sharp edge of mica at the base of the neck, the comparatively high rate of dissipation is not altogether surprising.

The expression for the natural frequency of a Helmholtz resonator (calculated without allowance for dissipation) is

$$N=\frac{V}{2\pi}\sqrt{\frac{c}{S}}.$$

If N is found from the resonance curve and S is measured, the conductivity c can be calculated, and this should be a constant for a given size and shape of neck. For the cylindrical necks 2·2 cms. long and 0·75 cm. in diameter, and partially obstructed by the platinum wire grid, it is found that c is about 0·13 cm. The following is an example of the kind of measurement taken :—

N. vibrations/sec.	S. c.c.	c cm.
240	68	0·133
235	73·6	0·138
140	197	0·131
116	290	0·132
Temperature 13°·3 C. Mean value of $c = 0\cdot 133$ cm.		

As a rough check on these observations, we may calculate from hydrodynamical principles approximate upper and lower limits to the conductivity of the neck. The required expression is given by RAYLEIGH ("Theory of Sound," vol. II., p. 181). For a cylindrical neck of length L and radius R,

$$c = \frac{\pi R^2}{L + \alpha R},$$

where αR is the "end correction" to be added to L on account of both ends. Since one end is flanged and the other unflanged, we take $\alpha = 0{\cdot}8 + 0{\cdot}6 = 1{\cdot}4$. To find an upper limit to c, take $L = 2{\cdot}2$ cms., $2R = 0{\cdot}75$ cm.; and for the lower limit take $L = 2{\cdot}2$ cms., $2R = 0{\cdot}65$ cm. (the diameter of the circular hole in the mica plate). We then find

$$0{\cdot}162 > c > 0{\cdot}125.$$

§ 5. *Sensitivity.*

The following experiment gives some idea of the smallness of the sound of which the microphone is capable of recording when it is used in conjunction with an amplifier. A microphone was constructed from brass-tubing 1 inch in diameter and tuned to respond to a note of 256 vibrations per second. This microphone was placed in one corner of a large field and connected by a long pair of leads to an army amplifier of the "C Mark II." pattern, the output terminals of which could be connected either to a pair of Brown telephones or to a Campbell vibration-galvanometer (also tuned to 256 vibrations per second). In order to test the sensitivity of the microphone, a tuning-fork giving a note of frequency 256 was sounded over a resonator at various distances from the microphone. The sound produced was as a rule inaudible to the unaided ear at distances greater than 80 yards. It could, however, be heard in the telephones up to distances of about 200 yards, and when the vibration-galvanometer was used quite well-marked deflections were obtained up to a distance of 400 yards or more.

As regards the conditions which determine the sensitivity of the microphone, these may be divided into two groups according to whether they have reference to the resonator or to the grid. We will deal first with those that refer to the resonator. Amongst them the most important is obviously that the resonator be accurately tuned to the note which it is required to record. The effect of mistuning is clearly shown by the resonance curve in fig. 5.

When the resonator is accurately tuned, *i.e.*, when $n = p$, the maximum velocity in the neck, according to the equations given in § 4, is

$$\left(\frac{dx}{dt}\right)_{\max.} = \frac{f}{2K}.$$

Since $f = \frac{c\mathrm{F}}{\rho}$, F being the variable part of the pressure at the mouth of the resonator, the actual "magnification" of the displacements and velocities obtained by using the resonator is seen to be

$$\frac{\mathrm{V}c}{2\mathrm{K}},$$

and is determined by the ratio of the conductivity of the neck to the damping factor K. Since, when c is constant, K is found to be larger the higher the pitch of the resonator employed, the efficiency of the microphone for the higher notes is correspondingly diminished.

As a numerical example, we may quote the case of the resonator used to obtain the curve in fig. 5, for which $\mathrm{N} = 240$ and $\mathrm{K} = 38 \cdot 5$, so that, putting $\mathrm{V} = 33760$ cm./sec. and $c = 0 \cdot 13$ cm., the "magnification" is about 57; while for a resonator of pitch 112, and $\mathrm{K} = 22 \cdot 2$, the "magnification" is about 100. It may be noted here for future reference that if $\mathrm{K} = 38 \cdot 5$, and the amplitude of the sound outside the resonator is $1 \cdot 27 \times 10^{-7}$ cms., *i.e.*, RAYLEIGH's value for the minimum amplitude audible when $\mathrm{N} = 256$, then the maximum velocity in the neck of the resonator will be about 0·0116 cm. per sec., and that, even if the amplitude is two hundred times the above value, the maximum velocity in the neck will still be less than 2·5 cms. per sec.

One of the most important factors in determining the efficiency of a resonator is the rigidity of the walls of the container. This was well shown by the following experiment.

A cylindrical resonator of rolled veneer was tested and found to respond to the same frequency as a brass resonator of the same volume with the same orifice. The resonant note was 79 vibrations per second. Experiment showed that its degree of response (measured with a Wheatstone's Bridge) was only one-third of that of the brass one, the conditions being as nearly as possible the same in both cases. The resonance curve for the veneer resonator showed that the appropriate value of K was about 35.

We have next to consider some points in connection with the sensitivity of the grid. Almost the first problem that arises in constructing a microphone of this pattern is the choice of a suitable diameter for the wire. In the first experiments that were made with microphones of this type the diameter of the wire used was 0·0015 cm. It was found, however, that better results were obtained with finer wire, and from time to time experiments have been carried out with wire of various diameters down to 0·0002 cm. These experiments showed that the finer the wire the greater was the sensitivity (more especially for high-pitched notes), but that the increased sensitivity obtained with very fine wires was very often counter-balanced by their extreme fragility, which rendered them unsuitable for anything but very special purposes. Finally, a wire of diameter about 0·0006 cm. has been adopted as being sufficiently sensitive, and at the same time not too fragile to prevent its being employed in ordinary out-of-door experiments.

The sensitivity is most easily controlled by altering the heating current. No matter

in what manner the microphone is employed, it is found that its sensitivity is always increased by increasing the working current. The curves in fig. 6 show this effect in

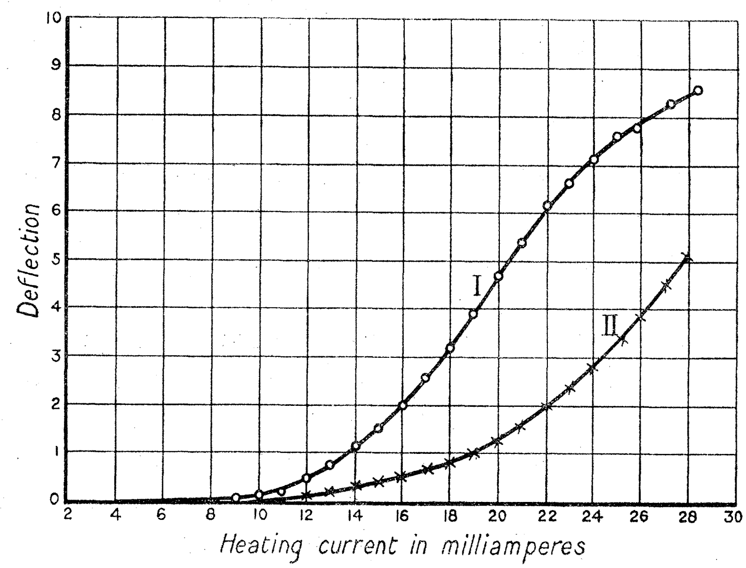

Fig. 6.

two cases : (1) when the microphone is connected in series with the primary of a transformer, the secondary of which is joined to a vibration-galvanometer ; and (2) when the microphone is employed with an amplifier and vibration-galvanometer.

The curves were obtained by clamping the microphone so that its orifice lay just between the prongs of an electrically maintained tuning-fork making 250 vibrations per second. The tuning-fork was carefully maintained at a constant amplitude while the heating current of the microphone was gradually increased from zero to the maximum safe current of about 28·5 milliamperes. In fig. 6 the heating current is plotted against the deflection of the vibration-galvanometer. Curve I refers to the case when the microphone is used with a transformer alone, while the effect of introducing an amplifier is shown by Curve II.* In the latter case, however, it must be borne in mind that the amplification itself is in all probability a function of the magnitude of the effect produced in the microphone. It will be observed that the effect produced by the sound is almost negligible until the heating current reaches a value of nearly one-third of the safe maximum.

In the case of the Wheatstone's Bridge, the effect of a change in the heating current of the microphone is complicated by the altered sensitivity of the Bridge. The variation of the sensitivity was therefore investigated by measuring the change in resistance of the grid with various heating currents for a given constant value of sound intensity. The method adopted in the experiment was as follows. A microphone was connected into a Wheatstone's Bridge circuit in the usual manner, and its resistance measured with various heating currents so that a current-resistance curve could be plotted. An electrically maintained tuning-fork, with a resonator to reinforce the sound, was then set

* For convenience the sensitivity of the galvanometer was reduced when using the amplifier.

in vibration at a convenient distance from the microphone. The amplitude of vibration of the tuning-fork could be observed through a microscope, and it was found that, with care, its amplitude could be maintained at a given value to within 2 or 3 per cent. A second series of observations of current and resistance of microphone grid was then made and the new current-resistance curve plotted on the same chart. The results obtained in a particular experiment are given in the following table :—

Without Sound.		With Sound.	
Current in milliamperes.	Resistance in ohms.	Current in milliamperes.	Resistance in ohms.
10·0	157·5	11·0	157·5
13·6	177·5	14·9	177·5
16·1	197·5	17·9	197·5
18·5	217·5	20·3	217·5
20·3	237·5	22·6	237·5
22·1	257·5	24·5	257·5
23·8	277·5	26·3	277·5
25·2	297·5	28·0	297·5
26·7	317·5	29·5	317·5
28·0	337·5		

The current-resistance curves are plotted in fig. 7. If, for some particular value of

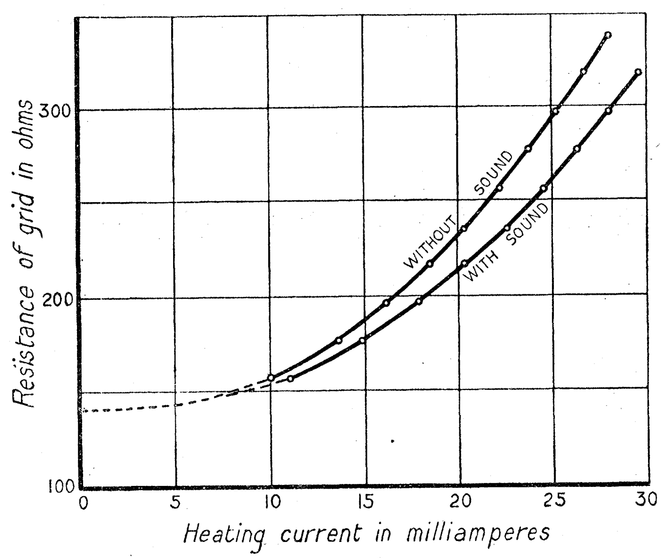

Fig. 7.

the heating current, the ordinate of the lower curve is subtracted from that of the upper curve, we find the change δR which the sound produces in the resistance of the grid

under the condition that the current remains constant. That is, δR is the change in resistance which would be measured if the bridge were re-balanced by inserting resistance in the microphone arm; or if a bridge of the "constant current" type is used, δR is simply proportional to the galvanometer deflection.

The relation between δR and R (the initial resistance of the grid), is a linear one, viz.:

$$\delta R = 0{\cdot}2\,(R-140),$$

140 ohms being the resistance of the grid at air temperature. Therefore, by altering R— or, what is the same thing, by altering the heating current—the sensitivity of the grid can be varied in a perfectly definite manner. Conversely, observations which have been made with the same microphone with different heating currents can be very easily made to correspond by reducing them to some standard value of the current. If observations are taken under different conditions of air temperature, a correction on this account can easily be made if desired.

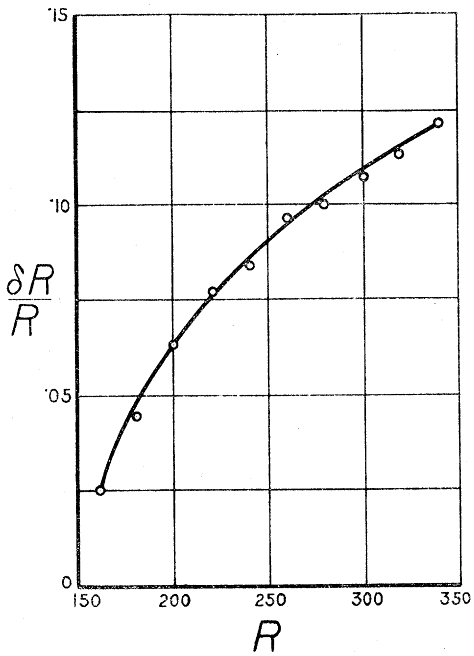

Fig. 8.

A quantity which is more characteristic of the wire from which the grid is made is $\frac{\delta R}{R}$, the change in resistance for a given sound in ohms per ohm. Probably the value of $\frac{\delta R}{R}$ for a given heating current and sound would provide the most convenient method of defining the sensitivity of a grid. The values of $\frac{\delta R}{R}$, obtained from the above table, are plotted against R in fig. 8, and show very clearly the way in which the sensitivity of the grid increases as its temperature rises.

§ 6. *The Resistance Changes in the Wire Grid.*

In this and the following two sections we shall examine more closely the means by which the platinum wire grid is enabled to record electrically the aerial vibrations which are set up in the neck of the resonator. Suppose in the first instance that a microphone is held with its axis vertical (neck uppermost), and that the grid is connected in series with a battery and the primary of the first stage transformer of an amplifier. It is found by experiment that the temperature of the platinum wire, when carrying its normal safe working current of about 29 milliamperes, is in the neighbourhood of 600° C., and we know that in these circumstances the energy supplied to the wire in

the form of heat is lost mainly by convection. There is in fact above the grid a free convection current whose velocity depends on the temperature and diameter of the platinum wire. A sound of suitable pitch produces in the neck of the resonator an alternating current of air which is superimposed upon the free convection current, with the result that the convection of heat from the platinum wire is alternately retarded and accelerated. It can easily be seen that if the maximum velocity of the alternating air-current does not exceed the velocity of the convection current, the periodic temperature change produced in the platinum wire will have the same frequency as that of the sound stimulating the resonator.

This is in accordance with the observed fact that when the microphone is held vertically the note heard in the telephones has the same pitch as that of the original sound.

Next, suppose that the microphone is held so that its axis is horizontal and the grid lies in a vertical plane. The free convection current is now at right angles to the axis of the neck, and the effect of an oscillatory motion of the air in the neck (parallel to its axis) will be to produce a periodic change in the temperature (and therefore resistance) of the grid whose periodicity will be twice that of the sound which produces it. This is in fair agreement with observations, for when the microphone is gradually tilted over from a vertical to a horizontal position, the fundamental note heard in the telephone slowly dies away and the octave becomes more and more prominent. The octave is heard best, however, when the neck is pointed slightly downwards so that the axis makes an angle of about 20 degrees with the horizontal. This peculiar effect, which appears to be due to the asymmetrical construction of the neck of the resonator, will be referred to in a later paragraph (§ 8).

We shall in the present section confine our attention to the case when the microphone is held vertically with the neck pointing upwards, and it will be assumed that the resistance changes which the sound produces in the grid can be attributed to the changes in the velocity of the air in the neck. In order to ascertain the nature of the resistance changes which are likely to occur, it is first of all necessary to determine the relation between the resistance R of the grid and the velocity U of the air-current which cools it. U here refers to the velocity of the forced air-current, the actual current passing the wires of the grid being the sum of the forced current and the free convection current. The velocity of the undisturbed convection current rising from the grid will not, of course, be evenly distributed in the neck of the resonator, but the effects of free convection can be represented by an "effective" current V_0 supposed uniform throughout the neck. The actual current passing the grid is then $V = U + V_0$, the downward vertical being regarded as the positive direction. We shall first obtain a relation between R and U for small steady values of U, and afterwards extend the results obtained to the case of oscillatory currents by putting $U \sin pt$ in place of U.

On account of the applications to be found in Hot-Wire Anemometry, the cooling of electrically heated fine platinum wires by steady currents of air has received a good deal

of attention from physicists. The most complete investigation available is that contained in the well-known paper by L. V. KING.* KING shows that, for fine wires in air-currents of low velocity, the heat-loss per cm. is given by an equation of the form

$$H = \alpha\theta_0/\log\frac{\beta}{Vd},$$

where α and β are constants, θ_0 is the excess temperature of the wire above its surroundings, V is the velocity of the air-current, and d the diameter of the wire. This equation is theoretically applicable whenever $Vd < 0{\cdot}0187$, a condition which is amply fulfilled in the present case with $d = 0{\cdot}0006$ cm. and V not greater than 6 cms. per second. We have not, however, been able to adapt this equation in any way which leads to useful results in the case of the Hot-Wire Microphone. It may be remarked that both the diameter of the wire and the magnitude of the air-currents with which we are concerned are considerably smaller than those used in the experiments of KING, or of other investigators to whose work reference will be found in KING's paper. In view of this fact, and of the rather special form of the grid and its mounting, it was thought desirable to determine experimentally the relation between R and U for such small values of U as are likely to be required to account for the behaviour of the grid under the influence of alternating air-currents.

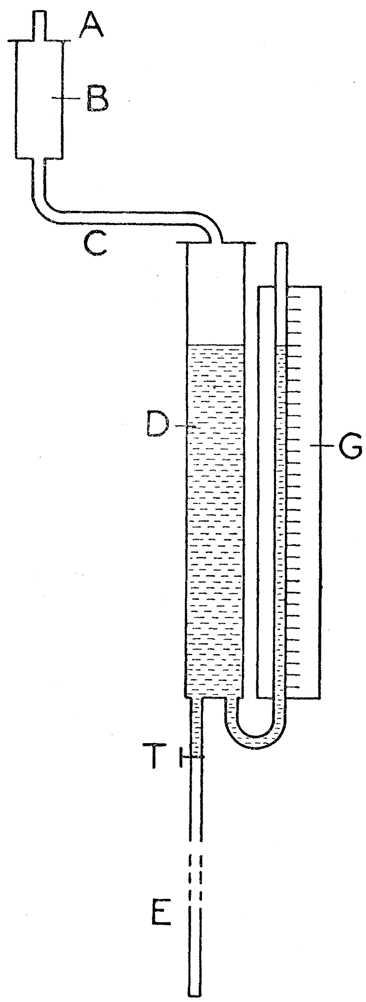

Fig. 9.

The arrangement of the apparatus used in the experiments is shown diagrammatically in fig. 9. A microphone grid is mounted in the holder at A. The interior of the small brass container (B), carrying the microphone and holder communicated by means of the short tube (C) with the reservoir (D), which was partly filled with water. A current of air could be produced past the microphone grid by opening the tap (T), which allowed the water in D to escape through the tube (E) into a second reservoir from 4 to 5 feet below D. A current in the reverse direction could be produced by allowing water to siphon into D from another reservoir at a higher level.

The average velocity of the air-current passing the grid was deduced from a knowledge of the area of the aperture in which the grid lies, the area of the cross-section of D,

* 'Phil. Trans.,' A, vol. 214, pp. 373–432 (1914).

and the velocity of the fall (or rise) of the surface of the water in D. The latter was found by timing the movement of the level of the water in the gauge (G). The maximum velocity of the fall or rise in D required in the experiments was 0·09 cm. per second, corresponding to a velocity of 6 cms. per second for the air passing the grid.

The microphone formed one arm of the Wheatstone's Bridge shown in fig. 4. The method of taking an observation was as follows. The balancing resistance R was given some prearranged value about equal to the sum of the resistance of the grid (carrying its normal current), the milliammeter and the variable resistance ρ set at 10 ohms. The resistance ρ could be varied by steps of 0·1 ohm from 0 to 20 ohms. With the tap (T) closed, the bridge was then balanced by adjusting the rheostat (Rh), that is, by altering the heating current until the total resistance of the microphone, milliammeter and ρ was equal to R. The tap (T) was then opened and adjusted to give an air-current past the grid of approximately the required velocity. The exact velocity of the air-current was determined by timing with a stop-watch the fall or rise of the level of the water in G for 1, 2 or 3 cm., according to the magnitude of the velocity employed. The change in the resistance of the grid was determined at the same time by increasing or decreasing the resistance ρ so as to restore the balance. The resistance-change was determined to 0·01 ohm by noting the deflection which remained after the bridge had been balanced as nearly as possible by altering ρ. The effect of a forced air-current on the resistance of the grid was thus determined under the condition that the electric current carried by the grid remains constant.

The results of one experiment are shown in the following table, which gives U, the impressed air-current, in centimetres per second, and δR the change in the resistance of the grid. The air-current U is taken as positive when it flows *into* the container—in this case vertically downwards.

MICROPHONE GRID A1079. Heating current 28·5 milliamperes. Resistance of grid when impressed air-current is zero = 270·8 ohms.

U. cm. per sec.	δR. ohms.	U. cm. per sec.	δR. ohms.
−4·12	−9·73	+0·27	+0·46
−3·54	−7·76	+0·53	+0·50
−3·13	−7·46	+0·55	+0·56
−3·04	−6·83	+0·90	+0·73
−2·20	−4·34	+1·33	+0·79
−2·07	−4·18	+1·40	+0·74
−1·65	−2·91	+1·97	+0·47
−1·33	−2·15	+1·99	+0·43
−0·74	−1·11	+2·40	+0·10
−0·48	−0·76	+2·67	−0·37
−0·45	−0·61	+3·61	−1·92
0	0	+4·30	−3·36

The values of U and δR are plotted in fig. 10 and a smooth curve drawn through the points. As the impressed air-current increases from zero the resistance of the grid

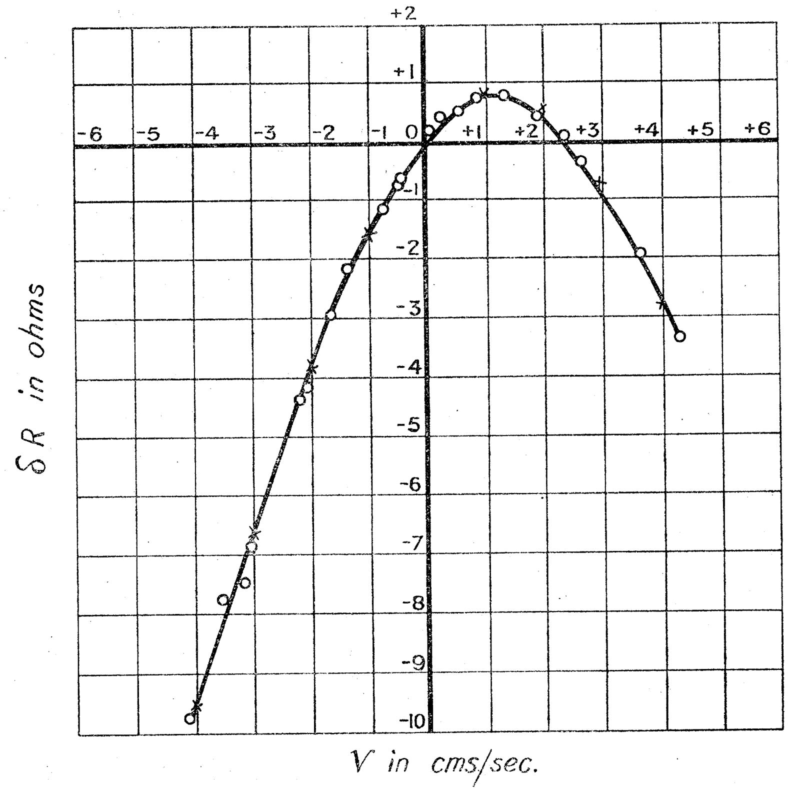

Fig. 10.

(given by $R = 270 \cdot 8 + \delta R$) rises and passes through a maximum, the curve cutting the U-axis at $U = 2 \cdot 45$ cms. per second. The maximum occurs when $U = \frac{1}{2} \times 2 \cdot 45 = 1 \cdot 225$ cms. per second. When U has this value, the impressed air-current balances the free-convection current V_0, so that $V_0 = 1 \cdot 225$ cms. per second. Somewhat similar curves to that in fig. 10 are given in a recent paper by J. S. G. Thomas,* who used this method to determine the velocity of free convection from a platinum wire 0·00784 cm. in diameter and carrying current of 0·6 to 1·2 amperes.

The symmetrical form of the curve about the line $U = V_0 = 1 \cdot 225$ suggests that the relation between δR and U can conveniently be represented by a formula of the type

$$\delta R = \delta R_0 + a\,(U - V_0)^2 + b\,(U - V_0)^4 + \&c.,$$

where δR_0 is the maximum *increase* in resistance occurring when $U = V_0$. It was found that the results of the above experiment could be very fairly represented by the formula

$$\delta R = 0{\cdot}74 - 0{\cdot}50\,(U - 1{\cdot}225)^2 + 0{\cdot}0044\,(U - 1{\cdot}225)^4.$$

A series of points for $U = 0, \pm 1, \pm 2$, etc., calculated from this expression, are indicated

* 'Phil Mag.', vol. **XXXIX**, pp. 518–523, and Pl. XI, fig. **II** (1920).

in fig. 10. In all such experiments, where U did not exceed 5 cms. per second, it was found that the result could be expressed within the errors of the experiment by a formula of the type

$$\delta R = \delta R_0 + a (U - V_0)^2 + b (U - V_0)^4.$$

In the above experiment the resistance was measured under the condition that the electric current carried by the grid was the same with and without the air-current. In many experiments, however, the cooling of the grid will be accompanied by an increase of electric current, which tends to restore the temperature to its initial value. The extent to which this takes place depends of course on the particular circuit in which the microphone is used, but in most cases its effect will not be very marked, owing to the dead resistance in series with the microphone.

In a second experiment, performed with a grid of similar type to that used in the first experiment, the resistance was measured for various values of U by rebalancing the bridge with the resistance R, so that the heating current did not remain quite constant but increased or decreased according as the grid was cooled or heated. The resistance Rh was 240 ohms. It was found that the resistance-velocity curve had the same character as that in the first experiment, and up to velocities of 5 cms. per second the change in resistance could be quite adequately represented by an expression of the above type.

It is convenient to write the expression for δR in the form

$$\delta R = -2V_0 (a + 2bV_0^2) U + (a + 6bV_0^2) U^2 - 4bV_0 U^3 + bU^4.$$

If the values of a, b and V_0 determined in the above experiment are inserted we get

$$\delta R = 1{\cdot}19U - 0{\cdot}46U^2 - 0{\cdot}022U^3 + 0{\cdot}0044U^4,$$

so that if U is not much greater than 1 cm. per second, δR is given by the first two terms to within 2 or 3 per cent.

In applying these results to the case of oscillating air-currents, we shall at first suppose that U is so small that the third and fourth terms are negligible. If it is assumed that the resistance of the grid at any instant is the "equilibrium" value which it would take up if the instantaneous velocity were maintained, then the changes in resistance produced by an alternating air-current U sin pt will be given by

$$\begin{aligned}\delta R &= -2V_0 (a + 2bV_0^2) U \sin pt \\ &\quad + (a + 6bV_0^2) U^2 \sin^2 pt \\ &= \tfrac{1}{2} (a + 6bV_0^2) U^2 \\ &\quad - 2V_0 (a + 2bV_0^2) U \sin pt \\ &\quad - \tfrac{1}{2} (a + 6bV_0^2) U^2 \cos 2pt.\end{aligned}$$

The total change would therefore be made up of three parts :—

(1) A steady drop in resistance given by $\delta R_1 = \frac{1}{2}(a+6bV_0^2)U^2$.
(2) A periodic change of resistance $\delta R_2 = -2V_0(a+2bV_0^2)U \sin pt$ of the same frequency as the sound stimulating the resonator.
(3) A periodic resistance change $\delta R_3 = -\frac{1}{2}(a+6bV_0^2)U^2 \cos 2pt$ of frequency twice that of the sound stimulating the resonator.

The relative importance of these effects can be gauged by putting in the values of a, b, and V_0 previously found. This gives

$$\delta R_1 = -0{\cdot}23U^2,$$
$$\delta R_2 = +1{\cdot}19U \sin pt,$$
$$\delta R_3 = +0{\cdot}23U^2 \cos 2pt.$$

These resistance changes correspond to the three most obvious effects of a sound of suitable pitch upon the microphone.

δR_1 is the effect made use of when the microphone is employed in a Wheatstone Bridge. Since it is proportional to U^2, that is, to the energy of the vibration in the neck, it should be proportional to the *intensity* of the sound-wave stimulating the microphone. This is confirmed by the experiments described in § 7.

δR_2 is the effect which causes the ripple on the heating current, and which can be made audible by the use of an amplifier. It will be seen that the amplitude of this effect is proportional to U, and therefore to the *amplitude* of the sound affecting the microphone. The extent to which this is confirmed by experiment is described in § 7. It should also be noted that the amplitude of the effect is proportional to V_0, the free convection current from the grid. It should therefore be possible to increase the loudness of the sound heard in the telephones by artificially increasing the steady air-current passing the grid. That this conclusion is correct can easily be demonstrated by gently heating the brass container with a flame so that a current of air is forced out past the grid.

The existence of δR_3, which should produce a note in the telephones an octave above the fundamental, is not easy to demonstrate when the microphone is held vertically. It cannot of course be heard in the telephones because it is completely swamped by the fundamental. When, however, the microphone is tilted the octave becomes relatively more important, and is easily heard at certain angles. These effects are described in § 9.

In order to discover what will occur in the case of very loud sounds, it will be necessary to use the more complete expression for δR which involves the third and fourth powers of U. Thus, writing the relation between δR and U for steady currents in the form

$$\delta R = a'U + b'U^2 + c'U^3 + d'U^4,$$

and substituting $U \sin pt$ for U, we find that the total resistance change can now be regarded as being made up of five parts, namely :—

$$\delta R_1 = \tfrac{1}{2} b' U^2 \left(1 + \tfrac{3}{4} \frac{d'}{b'} U^2\right),$$

$$\delta R_2 = a' U \left(1 + \tfrac{3}{4} \frac{c'}{a'} U^2\right) \sin pt,$$

$$\delta R_3 = -\tfrac{1}{2} b' U^2 \left(1 + \frac{d'}{b'} U^2\right) \cos 2pt,$$

$$\delta R_4 = -\tfrac{1}{4} c' U^3 \sin 3pt,$$

$$\delta R_5 = \tfrac{1}{8} d' U^4 \cos 4pt.$$

The interpretation of the various terms is obvious, and it remains only to estimate their relative importance. To do this, we can take as an example the grid examined in the experiment described above and use the numerical values of a', b', c' and d' already given. It will also be supposed that $U = 2 \cdot 5$ cms. per second, which, as previously shown (§ 5), would be the maximum velocity produced in the neck of the resonator if its natural frequency were 240 vibrations per second, and the amplitude in the primary wave were 200 times as great as the minimum amplitude audible. We find then that

$$\delta R_1 = -0 \cdot 23 U^2 (1 - 0 \cdot 0072 U^2) = -1 \cdot 37,$$

$$\delta R_2 = +1 \cdot 19 U (1 - 0 \cdot 014 U^2) = +1 \cdot 09 \sin pt,$$

$$\delta R_3 = +0 \cdot 23 U^2 (1 - 0 \cdot 0096 U^2) \cos 2pt = +1 \cdot 35 \cos 2pt,$$

$$\delta R_4 = +0 \cdot 0055 U^3 \sin 3pt = +0 \cdot 086 \sin 3pt,$$

$$\delta R_5 = +0 \cdot 00055 U^4 \cos 4pt = +0 \cdot 021 \cos 4pt.$$

So that, even with a comparatively loud sound, the notes of pitch three and four times the fundamental are quite unimportant.

One other point remains to be noted. From the expressions just given it can be seen that the simple rule, that δR_1 is proportional to the intensity of the sound stimulating the resonator, does not hold for very loud sounds. Similarly, the amplitude of the fundamental oscillatory effect is not proportional to the amplitude in the primary wave when very intense sounds are used. In both cases the effect with very loud sounds falls short of what it would be if the simple relations continued to hold.

§ 7. *Experiments on the Measurement of Sound.*

Two experiments will now be described which were undertaken with the object of testing the correctness of two of the conclusions arrived at in the previous section, viz. :—

(i) That the steady resistance change δR_1 is proportional to the intensity of the sound affecting the microphone ; and

(ii) That the amplitude of the oscillatory resistance change δR_2 is proportional to the amplitude of the sound which produces it.

As pointed out at the end of § 6, neither of these conclusions would be expected to hold quite exactly in the case of very loud sounds.

(i) *First Experiment.*—The object of the experiment was to find out if the change of resistance δR_1 is proportional to the intensity of the sound. In order to do this it is only necessary to expose a microphone to different sounds of known relative intensities, and to observe in each case the value of δR_1. The method adopted in the experiment was to observe the effect produced on the microphone when it was placed at various distances from a source of sound working at a constant rate, the relative intensities of the sound to which the microphone was exposed being deduced from the Inverse Square law.

The source of sound was an electrically maintained tuning-fork vibrating in front of a glass-bottle resonator, the frequency of the fork being 250 vibrations per second. The fork with its resonator was placed on the ground in a suitable open space.* The amplitude of vibration of the fork could be observed by means of a microscope and micrometer eyepiece, and it was found that with care the fork could be made to vibrate with an amplitude which would remain constant within a few per cent. for quite long periods of time.

The microphone was clamped with its axis vertical in a heavy retort-stand, so that it was held at a height of about 1 foot 6 inches above the ground. The grid was connected by a long pair of leads to a Wheatstone's Bridge, which was set up inside a laboratory. A reflecting galvanometer was used, and a preliminary experiment showed that for the small changes in resistance to be observed (not exceeding 0·25 ohm), the deflection shown by the galvanometer was proportional to the resistance change in the microphone.

The fork having been set in vibration, the stand carrying the microphone was placed at a convenient distance and the reading of the galvanometer noted. A piece of card was then placed over the mouth of the glass-bottle resonator, so that the sound from the fork became negligible. This enables the observer to obtain a zero reading on the galvanometer, the difference between the two readings being the deflection due to the sound. The microphone is then moved into another position at a greater or less distance from the fork and the process repeated. The result of one experiment is given below. The distances vary from 12 to 64 feet, and the deflections shown in the table are the means of three or four observations in each position. The actual readings for any particular distance did not differ amongst themselves by more than 0·3 cm.,

* The experiment was carried out on Woolwich Common, about one hour after sunset on a calm evening.

except in the case of the first two deflections, when the maximum variation was 0·5 cm.

Distance in feet.	Deflection in centimetres.	Distance in feet.	Deflection in centimetres.
12	13·0	36	1·7
16	9·1	40	1·4
20	5·7	44	1·1
24	3·3	48	0·85
28	3·0	56	0·8
32	2·3	64	0·6

In fig. 11 the deflection d is plotted against the distance r. By plotting log d against log r we obtain a straight line represented by

$$\log_{10} d = 3 \cdot 34 - 2 \log_{10} r,$$

which shows that the deflection d is proportional to $\frac{1}{r^2}$, that is, to the intensity of the sound.

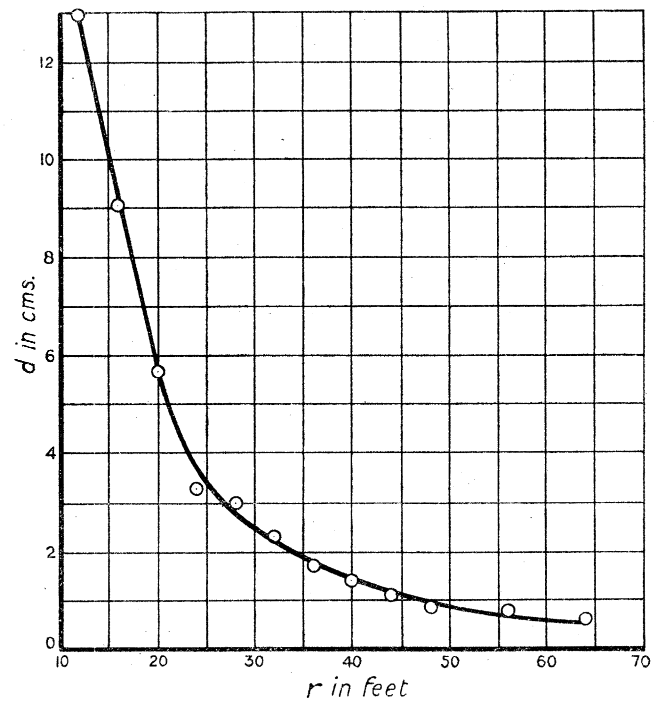

Fig. 11.

According to the equations given in § 6, we should have

$$\delta R_1 = -0 \cdot 23 U^2 (1 - 0 \cdot 0072 U^2)$$

for all values of U up to about 4 cms. per second. It becomes of interest to estimate

what is the probable maximum value of U in the above experiment. It was found that the sound from the fork was certainly inaudible to the unaided ear at a distance of 250 feet, this being probably rather an over-estimate of the distance at which the sound was just lost. Taking the amplitude of the sound at this distance to be $1 \cdot 27 \times 10^{-7}$ cms. (RAYLEIGH'S value for the minimum amplitude audible when the note is 256), we find that the amplitude of the sound at 12 feet from the fork is about $2 \cdot 7 \times 10^{-6}$, so that the maximum value of velocity in the sound-wave does not exceed 0·005 cm. per second, and the maximum velocity U of the air in the neck of the resonator will probably not be greater than 0·3 cm. In this case the effect of the second term in the expression for δR_1 is negligible.

A second experiment performed on another occasion under almost identical conditions confirmed the results already obtained. The distances employed in this experiment, however, did not exceed 32 feet.

(ii) *Second Experiment.*—The expression deduced in § 6 for the oscillatory resistance-change of the same frequency as that of the sound is

$$\delta R_2 = a'U\left(1+\tfrac{3}{4}\frac{c'}{a'}U^2\right)\sin pt,$$

where $\frac{3}{4}\frac{c'}{a'}$, is very small, so that, except for exceedingly loud sounds,

$$\delta R_2 = a'U \sin pt.$$

In the case of experiments such as that just described, we may write

$$\delta R_2 = \frac{A}{r}\sin pt,$$

since δR_2 is proportional to the amplitude of the sound affecting the resonator.

When an amplifier is used as a means of observing this effect, its working depends in the first place on the fluctuation of the current in the primary circuit. The effect of the small oscillatory resistance change in the microphone is to produce a " ripple " on the steady heating current, the amplitude of which to a first approximation is proportional to the amplitude of the oscillatory resistance change. Without considering the processes by which this ripple is amplified by the series of transformers and thermionic valves which constitute a transformer amplifier, we shall at once proceed to enquire by an experimental method whether the amplitude of the current on the output side of the amplifier is proportional to the amplitude of the sound affecting the microphone. It is perhaps scarcely necessary to point out that in such an experiment it cannot be assumed that the amplification is constant for different values of the amplitude of the ripple. For ripples of very small amplitude, however, it seems probable that the amplification may be sensibly constant over a moderate range. In spite of these difficulties, which make the interpretation of the observations somewhat obscure, the results obtained appear to be of sufficient interest to justify their inclusion in this paper.

The general procedure followed in the experiment was similar to that already described. The Wheatstone's Bridge was replaced by an Amplifier of the Army pattern known as "C Mark II.," the output terminals being connected to a Campbell vibration-galvanometer tuned to respond to 250 vibrations per second. The source of sound was the same as before. It was not necessary in this case to take a zero reading for each position of the microphone.

The results of two experiments, carried out on different occasions and with different strengths of the source, are given in the following table:—

Experiment A.		Experiment B.	
Distance in feet.	Deflection in centimetres.	Distance in feet.	Deflection in centimetres.
8	11·4	20	10·1
12	9·0	24	7·3
16	7·2	28	6·1
20	6·0	32	5·6
24	5·4	36	4·8
28	5·1	40	4·4
32	4·6	44	4·2
36	4·2	48	4·1
40	3·8	52	3·9
44	3·2	56	3·7
48	3·0	60	3·0
		64	2·7

The curves A and B (fig. 12) show the results of plotting the observations in

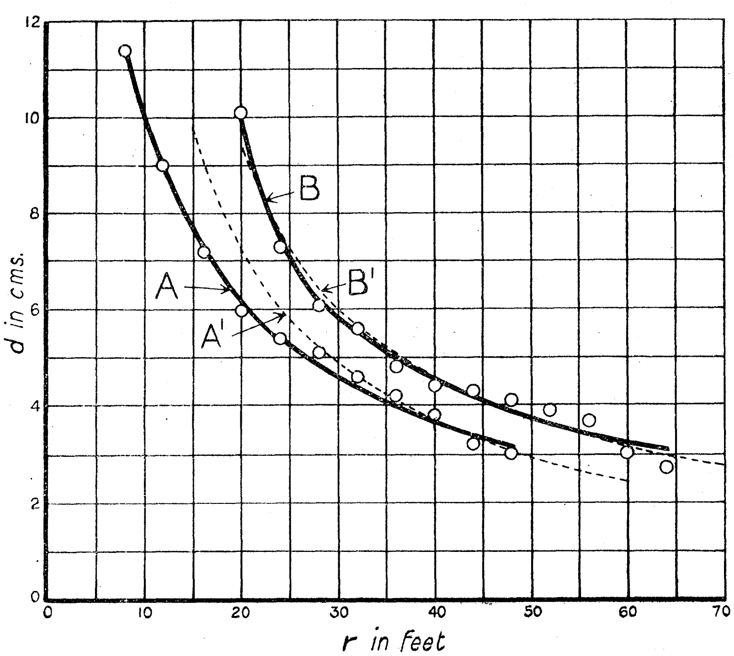

Fig. 12.

experiments A and B respectively. The curve A′ (fig. 12) is calculated from $d = \frac{146 \cdot 3}{r}$. It will be seen that the observed curve A lies along A′ when r is greater than about 28 feet, that is, when the sound has fallen below a certain amplitude. When r is less than 28 feet, the amount of deflection is less than it would have been had the simple inverse first-power rule continued to hold. This is indeed what might be expected from a consideration of the action of the microphone grid, as pointed out at the end of § 6, but the observed falling off in deflection is too great to be accounted for in this way alone.

In experiment B (curve B, fig. 12), the agreement between the observations and the relation $d \propto \frac{1}{r}$ is better. The broken curve B′ is calculated from $d = \frac{185 \cdot 4}{r}$.

Although the deflection corresponding to a given value of r is greater in the B curve than the A curve, it must not be inferred that the sound was louder in the former case. The deflection obtained depends not only on the loudness of the sound but also on the sensitivity to which the amplifier is adjusted and which can be varied over a very wide range. As a matter of fact the sound was louder in the A than in the B experiment. It may also be noted that in both cases the sound was louder than in the Wheatstone's Bridge experiment.

To sum it up, it may be said that the available evidence points to the fact that, when the microphone is employed with an amplifier and vibration galvanometer and only very faint sounds are observed, the deflection shown by the galvanometer is approximately proportional to the amplitude of the sound.

§ 8. *The Effect of Tilting the Microphone.*

It has already been mentioned that, when taking sound measurements with a Hot-Wire Microphone, it is necessary to keep the axis of the microphone inclined at some fixed angle to the horizontal. In fig. 13 a curve has been given showing the relation between the resistance of the grid and the angle of inclination of the axis to the vertical, the electric current carried by the grid being maintained at a constant value throughout the measurements. It is obvious from this curve that the tilt of the axis must not be altered while measurements are being taken by the Wheatstone's Bridge method.

The two most noticeable features about the curve are :

(i) That the resistance of the grid is less when the microphone is held upside down ($\theta = \pi$) than when it is in its normal upright position ($\theta = 0$), although in both cases the plane in which the grid lies is approximately horizontal ; and

(ii) That the resistance is least—that is, the rate of cooling is greatest—when θ is somewhat greater than $\frac{\pi}{2}$.

These two experimental results are curious and difficult to explain. They are both,

however, quite characteristic of the form of microphone under discussion, and cannot be attributed entirely to adventitious circumstances, such as the bending of the wire loops of the grid out of their normal positions.

Another point which may be noted is that, since the disposition of the loops about the axis of the microphone is not symmetrical, a rotation of the microphone about its own axis produces a change in resistance. It follows from this that when observations such as those shown in fig. 13 are continued for values of θ between 0 and $-\pi$, the curve is not in general symmetrical about the line $\theta = 0$.

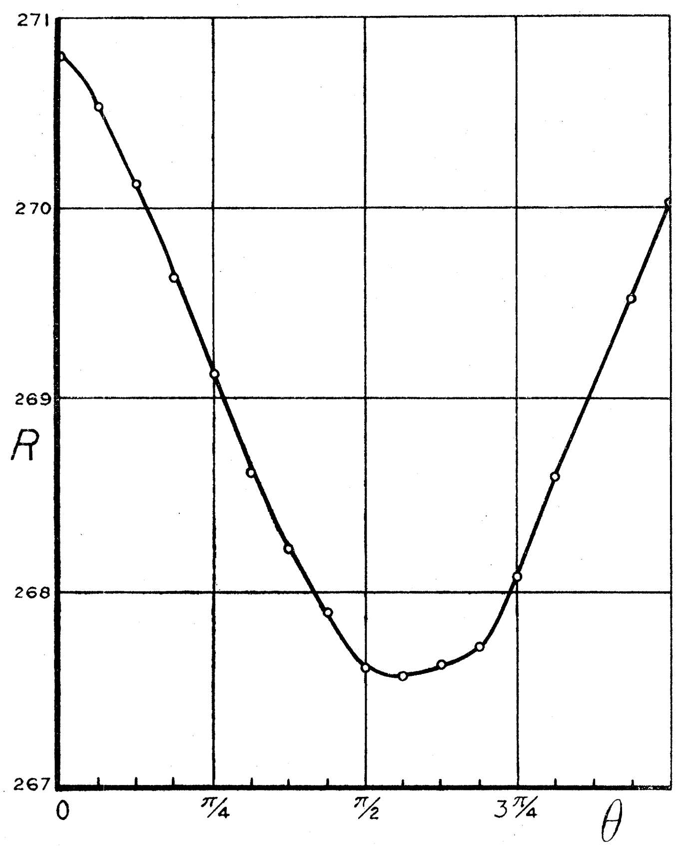

Fig. 13.

It is clear from these results that the resistance of the grid depends, not only on the magnitude of the current of air by which it is cooled, but also on the direction of this current relatively to the plane in which the grid lies. This is due to the free convection from one part of the grid acting upon another part, and is essentially the same phenomenon as that used by J. S. G. THOMAS in the construction of a "Hot-Wire Inclinometer."*

When the Amplifier method is used it is found, as stated previously, that the effect of tilting the microphone is to change the character of the sound heard in the telephones. As θ is increased from 0 to $\frac{\pi}{2}$ the fundamental note becomes gradually weaker, while

* "An Electrical Hot-Wire Inclinometer," by J. S. G. THOMAS, 'Proc. Phys. Soc.', Lond., vol. XXXII., pp. 291–314 (1920).

at the same time the octave becomes more and more prominent. For some value of θ exceeding $\frac{\pi}{2}$, but varying somewhat with different grids and the way in which the microphone is held, the fundamental is almost suppressed and the octave is heard with corresponding clearness. When θ is still further increased the fundamental becomes gradually restored, and the sound of the octave is altogether lost to the ear when $\theta = \pi$. The value of θ at which the octave is most clearly heard (generally between 110° and 120°) is altered slightly if the microphone is rotated about its own axis.

To demonstrate this effect, a microphone (M) was mounted with its neck projecting into a tube (TT) (fig. 14), which could be rotated about a horizontal axis. When so rotated the axis of the microphone could be inclined to the vertical at any desired angle, while the open ends of the tube (TT) were exposed to the same amount of sound throughout the experiment. The microphone was connected to an amplifier in the usual manner, and the output terminals of the amplifier were joined to a vibration galvanometer. The source of sound used was an electrically maintained tuning-fork making 250 vibrations per second, the microphone and vibration galvanometer being also tuned to this frequency.

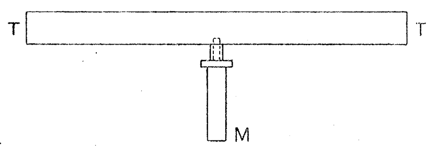

Fig. 14.

The curve in fig. 15 shows the deflection of the vibration galvanometer plotted

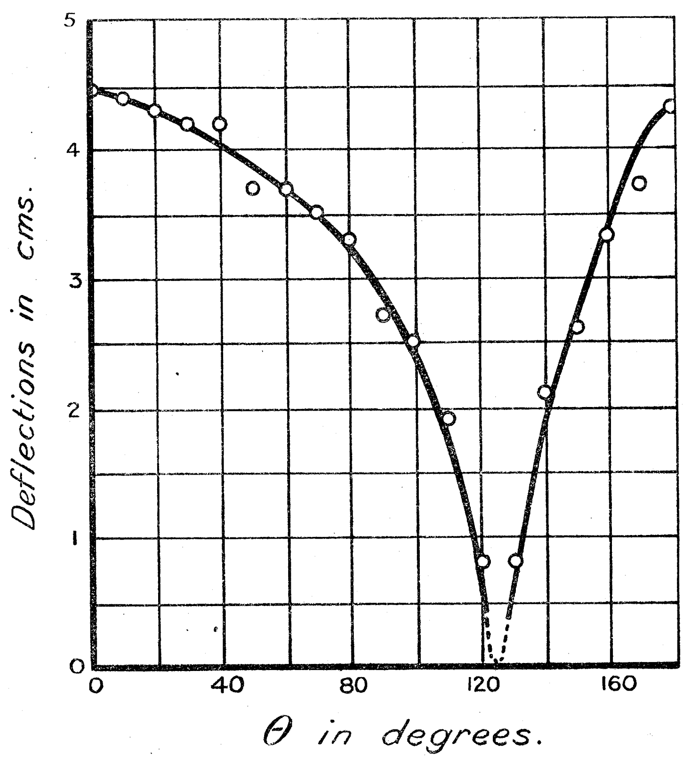

Fig. 15.

against θ, and demonstrates clearly that the amplitude of the fundamental vibration passes through a minimum when θ is about 125°.

An application of the experimental method of investigation described in § 6 leads to some interesting results. For example, an experiment was performed to determine the relation between the resistance R of the grid and the impressed velocity U of the air-current when $\theta = \frac{\pi}{2}$. The results are given in the following table. The value of θ indicates only the tilt of the axis of the container and neck, and does not necessarily mean that the plane containing the loops is exactly vertical.

MICROPHONE GRID A1079. Heating current 28·5 milliamperes. Resistance of grid when impressed air-current is zero = 266·85 ohms.

U. cm. per sec.	δR. ohms.	U. cm. per sec.	δR. ohms.
−5·54	−9·25	+1·04	+0·002
−4·22	−6·21	+1·11	−0·02
−4·15	−5·64	+1·58	−0·31
−2·98	−2·92	+2·15	−0·84
−2·32	−1·78	+3·48	−2·99
−1·36	−0·93	+4·49	−5·46
−1·17	−0·70	+5·11	−6·51
−0·64	−0·34		

These observations are shown graphically in fig. 16.

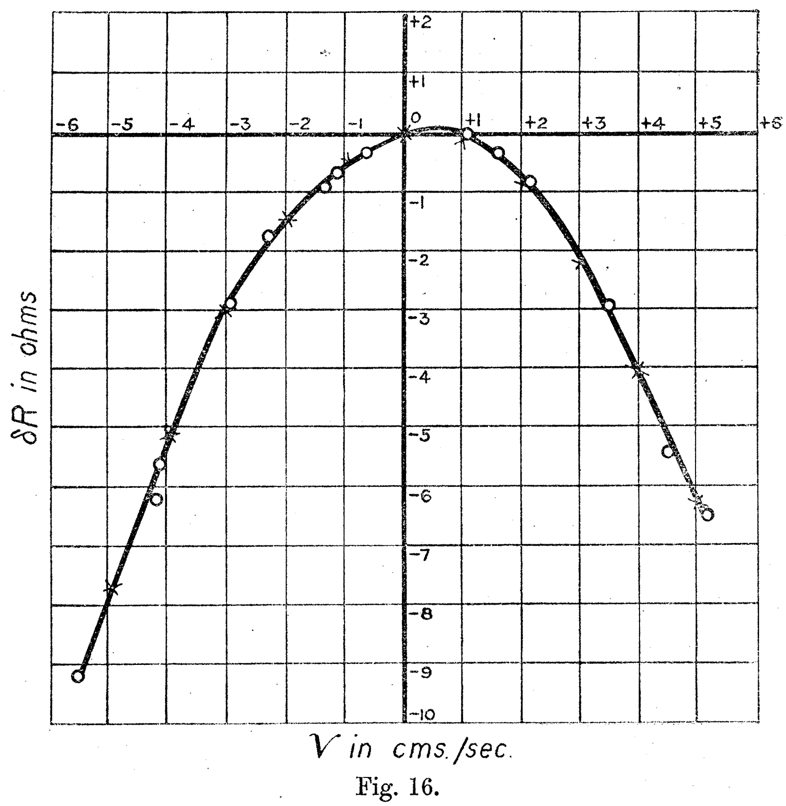

Fig. 16.

Assuming, as in the case when the microphone axis is vertical, that the relation between U and δR can be put in the form

$$\delta R = \delta R_0 + a(U - V_0)^2 + b(U - V_0)^4,$$

we find that a fair agreement is obtained when

$$\begin{aligned} \delta R_0 &= +0{\cdot}02 \\ a &= -0{\cdot}3 \\ b &= +0{\cdot}0007 \\ V_0 &= +0{\cdot}25 \end{aligned}$$

that is,

$$\delta R = 0{\cdot}02 - 0{\cdot}3(U - 0{\cdot}25)^2 + 0{\cdot}0007(U - 0{\cdot}25)^4.$$

Points calculated from this formula when $U = 0, \pm 1$, etc., are shown by the crosses in fig. 16. It will be seen that the fit is not so good as in the case when the microphone was held vertically (fig. 10), and also that the experimental curve is not quite symmetrical about the line $U = V_0 = 0{\cdot}25$ when U is small. It is, however, difficult to obtain reliable readings of the resistance of the grid when the microphone axis is horizontal or nearly so, and the above formula appears to represent the experimental results sufficiently well for the present purpose. It may be written

$$\delta R = +0{\cdot}15U - 0{\cdot}3U^2 - 0{\cdot}00035U^3 + 0{\cdot}0007U^4,$$

and by putting $U \sin pt$ in place of U, and disregarding the terms in U^3 and U^4, it can be seen that the three principal effects to be expected when the microphone is exposed to a sound-wave of suitable frequency are

$$\begin{aligned} \delta R_1 &= -0{\cdot}15U^2, \\ \delta R_2 &= +0{\cdot}15U \sin pt, \\ \delta R_3 &= +0{\cdot}15U^2 \cos 2pt. \end{aligned}$$

If these are compared with the corresponding expressions in § 6, it will be seen that for a given value of U the magnitude of the steady resistance change and the amplitude of the octave are reduced in the proportion 15/23, but that the amplitude of the fundamental vibration is reduced to 15/119 of its value when $\theta = 0$. Although, therefore, all these effects are diminished when the microphone is laid horizontally, it is the fundamental vibration which suffers the most. So far the deductions made from the results of the experiments with steady air-currents are in accordance with observation.

For values of θ between 0 and $\frac{\pi}{2}$, curves intermediate in form between those in figs. 10 and 16 are obtained. When θ is greater than 0, V_0 no longer represents the velocity

of free convection from the grid, but is more nearly the component of the free convection along the axis of the microphone. That is, V_0 is approximately equal to $\overline{V}\cos\theta$, $\overline{V}$ being the velocity of free convection from the grid. If this were strictly true, we should have $V_0 = 0$ when $\theta = \frac{\pi}{2}$, but this is not generally the case, probably owing to the fact that the loops are slightly displaced and do not lie in a plane which is just at right angles to the microphone axis, and it may even happen that they are not all in the same plane. For example, in the case of the grid used in the experiment just described, it was found that

$$V_0 = 1\cdot225 \text{ cms. per second when } \theta = 0,$$

and

$$V_0 = 0\cdot25 \text{ cm. per second when } \theta = \frac{\pi}{2}.$$

As an approximation we may take $\overline{V} = 1\cdot225$ and $V_0 = \overline{V}\cos(\theta+\alpha)$ when θ is near $\frac{\pi}{2}$, so that

$$1\cdot225\cos\left(\frac{\pi}{2}+\alpha\right) = 0\cdot25.$$

Whence

$$\alpha = -11^\circ,$$

and we should have $V_0 = 0$ when $\theta = 101^\circ$.

When $V_0 = 0$ the expressions for the resistance changes produced by an oscillatory air-current (§ 6) reduce to

$$\delta R_1 = \tfrac{1}{2}aU^2,$$
$$\delta R_2 = 0,$$
$$\delta R_3 = -\tfrac{1}{2}aU^2\cos 2pt,$$

so that the total resistance change is made up of two parts only—a steady change and the octave—while the fundamental vibration is completely suppressed. Now the curve in fig. 15 shows that in that particular experiment the fundamental was suppressed when θ was about 125 degrees, and this is indeed about the usual value of θ for this phenomenon to occur, while (as in the above example) V_0 vanishes when θ is at most about 100 degrees. It appears therefore, that merely writing $U\sin pt$ instead of U, in the equation connecting U and δR for small steady velocities, does not in this case explain all the observed phenomena.

A satisfactory explanation of this difficulty has not yet been found, but the hypothesis that a jet may be formed in the neck of the resonator may be put forward. The possibility of this occurring in the mouths of ordinary resonators is discussed by RAYLEIGH ("Theory of Sound," vol. II., § 322). If a jet were formed in the neck of the resonator, then, in order to account for the observed phenomenon, it would have to

be of such a nature that the outward movement of the air takes place principally along the central axis of the neck, while the inward movement takes place close to the walls of the neck. Since the platinum grid is placed centrally in the neck and does not occupy any space near the walls, the effect of the jet could be represented by adding a term V' to V_0, so that (approximately)

$$V_0 = \overline{V} \cos(\theta+\alpha) + V'.$$

The fundamental would then be suppressed when

$$\overline{V} \cos(\theta+\alpha) + V' = 0.$$

If $\alpha = -11°$ (as in the case of the grid used in the experiment described above), then θ will be 125° if $\frac{V'}{\overline{V}} = 0 \cdot 4$.

A further point in favour of this hypothesis is, that the angle at which the microphone must be tilted for the octave to be heard best depends to some extent on the intensity of the sound.

On the other hand, if a jet were formed, then since the amplitude of the fundamental is approximately proportional to V_0, the amplitude when $\theta = 0$ should be to the amplitude when $\theta = \pi$ in the approximate ratio $\frac{\overline{V} + V'}{\overline{V} - V'}$. And since we must have $\frac{V'}{\overline{V}}$ about equal to $0 \cdot 4$ in order to make $\theta = 125$ degrees when the octave is heard best, it follows that the microphone should be more than twice as sensitive to the fundamental vibration when it is held upright than when it is held upside down. This is not borne out by experiment, which shows that the sensitivity is only slightly reduced by turning the microphone upside down (see fig. 15).

RAYLEIGH* points to the near agreement between observed and calculated pitch in support of his view that jets are not formed "to any appreciable extent at the mouths of resonators as ordinarily used." The further argument, however, that "the persistence of the free vibration . . . seems to exclude any important cause of dissipation beyond the communication of motion to the surrounding air," does not apply to the resonators used in the present experiments, for it is shown in § 4 that the dissipation caused by the communication of motion to the surrounding air is negligible compared with the total amount of dissipation which occurs.

It appears, therefore, that the jet hypothesis, while offering a plausible explanation of the suppression of the fundamental at such large values of θ as 125 degrees, is open to objection on account of

(i) The nearly equal sensitivity shown by the microphone in the erect and inverted positions ; and

(ii) The near agreement between observed and calculated pitch (see § 4).

* *Loc. cit.*, p. 217.

§ 9. *Some Observations of Distribution and Intensity of Sound made with the Hot-Wire Microphone.*

The applications of the microphone to sound measurements are sufficiently numerous to justify a short description. It is quite obvious that the apparatus is not adapted to the measurement of the total quantity of a medley of sounds, since the microphones are selective, and the pitch or wave-length of the sound measured must therefore always be given.

Full advantage can be taken of the two alternative methods of using the microphone for sound measurement. In general, it should be laid down that the Wheatstone's Bridge method should be adopted for cases in which the sound distribution can be altered by keeping the microphone fixed in space and changing the position of the source of sound or by movement of any screen, reflector, trumpet, etc., while source and microphone occupy given positions.

If, however, the microphone has to be attached to some moving object the amplifier method has to be employed, records of amplitude being given by a vibration galvanometer, or in certain cases by rectifying the current and using a reflecting galvanometer.

The simplest experiment to perform is that of observing the distribution of intensity of sound in a closed room. By the Wheatstone's Bridge method the microphone can occupy some fixed position while a steady source of sound such as a tuning-fork is carried about the room.

The effects are sufficiently strong for a pivoted galvanometer to be employed for observation.

A variant of this experiment is to keep the source of sound in one place, and observe the effects of moving either one's self, of altering the position of furniture in the room, or of opening of doors or windows. It is quite easy to vary these arrangements in such a manner as to reduce the intensity of sound as recorded by the microphone from a maximum value to zero. The position of nodes and antinodes in the room can be investigated by moving the microphone and employing the amplifier method with telephones or vibration galvanometer. The results obtained are sufficiently striking to condemn any method of sound measurement in a closed room—the mere movement of the observer being sufficient to vitiate any experimental results. Methods of ear testing, which so commonly employ tuning-forks, are equally unsatisfactory. All measurements must therefore be made in the open-air and full precautions must be taken to avoid obstacles presenting reflecting surfaces.

Moreover, open-air work can only be performed under exceptionally calm conditions such as exist on certain nights or during a fog.

These phenomena are of far reaching importance in architectural acoustics. It seems evident that in any room or concert hall there is a considerable difference between the musical piece as rendered by instruments and the sounds which the audience observes; and it also follows that various members of the audience hear the same rendering

somewhat differently owing to their positions in the room. That the sensation of suppression of a note is not obvious is no doubt due in some measure to the distance between the two ears.

Experiments on Reflection.—A large sheet of uralite was set up out of doors with its plane vertical. An electrically driven tuning-fork served as the source of sound, and was mounted opposite the centre of the uralite at a distance of 30 feet from it. The sound was thus incident normal to the surface and capable of producing stationary waves.

The curve connecting deflection of the galvanometer and distance from the reflector is shown in fig. 17 and indicates clearly the position of nodes and antinodes. The

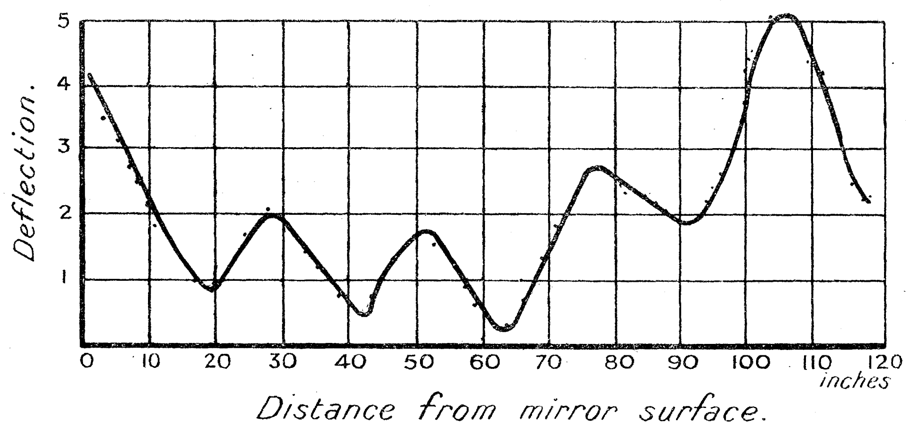

Fig. 17.

distance between the nodes agrees well with that obtained from a wave-length of 43 inches, except for that nearest to the mirror. All observations taken with various surfaces showed that the first antinode was nearer the mirror surface than was anticipated, which may be due to the lack of rigidity of the reflecting surface. The effect at the reflecting surface varies very largely with its nature; thus, when a wooden door is employed, the effect is greatest at the centre of the door midway between the four panels and least at the panels where there is minimum rigidity.

The reflecting qualities of different surfaces for sound can thus be compared. It is also obviously a simple matter to test the transmitting properties of various media—taking care to confine the sound transmitted to the material under test.

Experiments with Trumpets.—A trumpet has certain magnifying and directional properties, which depend on its dimensions and the wave-length of the sound employed; and another important factor in magnification is the material of which the trumpet is made. In the experiments described below the trumpet employed was conical, having a mouth 18 inches in diameter, a throat $\frac{1}{2}$ inch in diameter and a slant side of $25\frac{1}{2}$ inches. It was made of 1-inch wood in 16 segments.

The trumpet was mounted on a stand with its axis horizontal, and was capable of rotating about a vertical axis, its bearing being indicated by a pointer travelling over a horizontal circle graduated in degrees. The narrow end of the trumpet received the

aperture of a resonant microphone, and the connection with the trumpet was such as to leave unchanged the resonant note of the microphone by modification of its orifice.

The source of sound was the electrically maintained tuning-fork previously referred to and its distance from the trumpet was 50 yards. In order to enhance the source of sound the prongs of the tuning-fork were caused to set in resonant vibration the air in a glass bottle, and the mouth of the bottle was taken as the position of the source.

To get the zero of bearing, cross-threads were fixed to the trumpet mouth so that they coincided with two perpendicular diameters of the mouth. A small sighting-hole was drilled in a brass plate covering the narrow end of the trumpet. By looking through this aperture and rotating the trumpet until the cross-threads appeared in line with the source one was able to observe the zero of bearing on the scale.

The following table gives readings of the vibration galvanometer for various orientations of the trumpet :—

Bearing in degrees.	Deflection in divisions.	Bearing in degrees.	Deflection in divisions.
0	48	50	36
5	48	55	34
10	47·5	60	31
15	47	65	28
20	46	70	25
25	45	75	22
30	43·5	80	18·5
35	42	85	15
40	40	90	11
45	38		

It is interesting to note that the intensity of sound at the throat of the trumpet increases again as the bearing approaches 180 degrees and gives a maximum. Such an effect can be easily observed by fitting a stethoscope to the narrow end of the trumpet and listening by ear as the trumpet is rotated.

When the trumpet is removed and the sound recorded by a microphone alone, an estimate of magnification is given. It was found that the ratio

$$\frac{\text{Maximum deflection with the trumpet}}{\text{Deflection without the trumpet}} = 14 \cdot 5,$$

which is a measure of amplitude magnification, since it has been shown in § 7 that deflection is proportional to amplitude.

The diagram (fig. 18) shows the nature of the polar curve of amplitudes. Experiments with sources of different pitches indicated that the higher the pitch the sharper the curvature in the region of the zero bearing. For highly directive apparatus, therefore, every advantage is to be gained by using big trumpets.

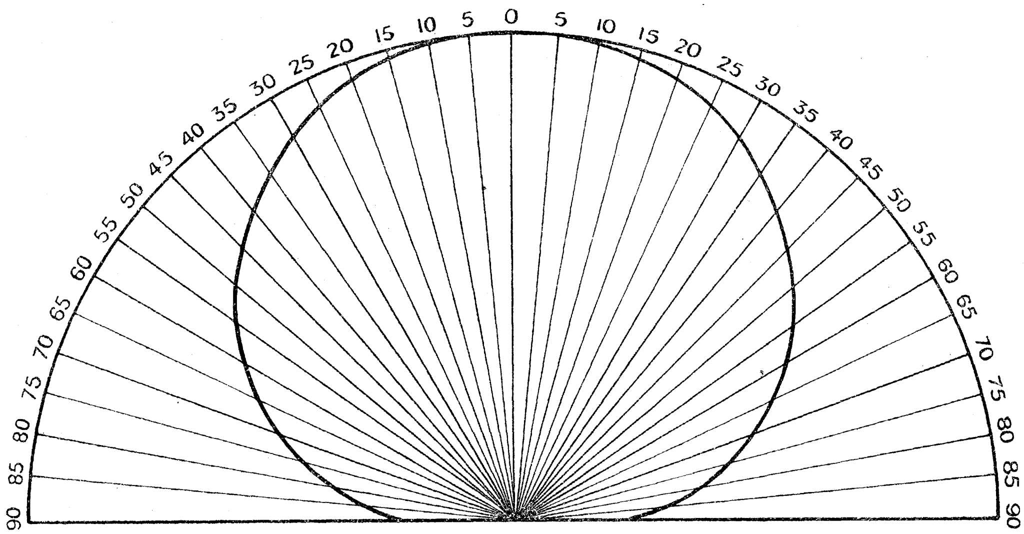

Fig. 18.

The Hot-Wire Microphone gives an easy method of testing the resonance frequencies of trumpets, but the effect must not be complicated by using a resonant microphone of the type described above. In this case the trumpet itself may be used as the resonating cavity. A bare grid with an orifice of the type above described is fitted to the narrow end of the trumpet, as shown in fig. 19, and the amplifier is used with rectifier and

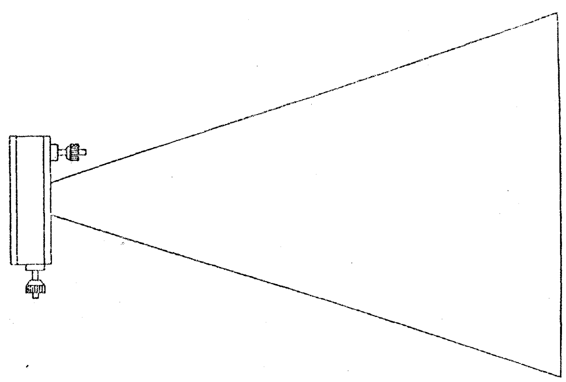

Fig. 19.

reflecting galvanometer. The bridge method cannot be employed in this case as the open trumpet is subject to draughts, and there is constantly a movement of air in one direction or the other which would cause a change in resistance of the heated grid.

The source of sound is the specially constructed siren referred to in § 4. As the pitch

rises a deflection is produced in the neighbourhood of resonance. The diagram (fig. 20) shows a relation between the pitch of the siren note and the response of the

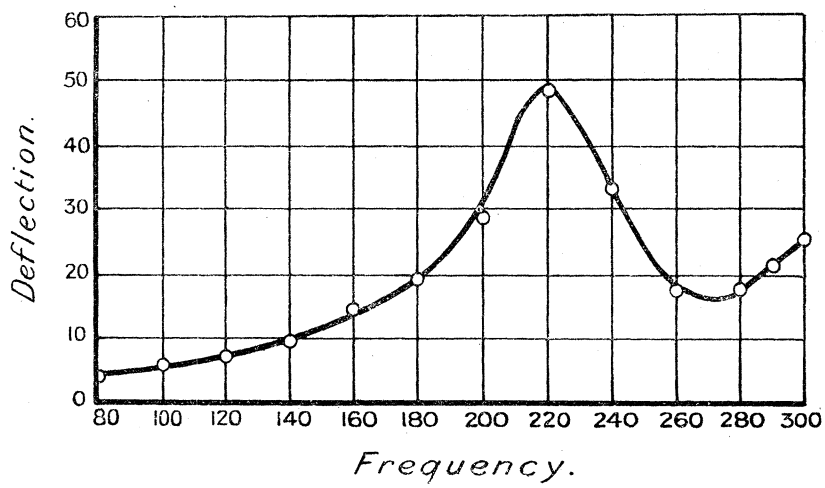

Fig. 20.

trumpet. The amount of resonance is expressed in terms of galvanometer deflection as shown by the following table :—

Frequency (vibrations per sec.).	Deflection (divisions).	Frequency (vibrations per sec.).	Deflection (divisions).
80	3	200	30
100	5·5	220	49
120	7·5	240	32
140	10	260	17
160	13	280	16
180	20	300	24

The table shows an upward curve at the highest frequency, thus indicating approach to the next overtone. The maximum at 220 indicates the fundamental resonance note.

By means of the microphone, therefore, the whole properties of a trumpet as a receiver of sound can be investigated, both as regards directive action and resonance.

Since by the principle of reversibility we may employ the trumpet as a transmitter for any given note, we may also derive its properties as a distributor and magnifier of any sound produced at the narrow end.

This has an obvious application to gramophone trumpets, in which the diaphragm acts as the source of sound.

In conclusion, one example may be given of the use of the microphone to measure diffraction of sound.

An interesting example is that of the diffraction effect of a single disc. A large wooden disc, 1 inch thick and 10 feet in diameter, is suspended by one edge. The tuning-fork described above serves as a steady source of sound and is placed opposite the centre of the disc and 30 feet from it. The microphone, in tune with this fork, is mounted with its orifice at the centre of the back of the disc—the axis of the microphone being of course vertical. The disc, with microphone, is now swung round about its vertical diameter and readings are taken with the vibration galvanometer—using the Amplifier method. The bearings were observed by means of a sighting-tube passing normally through the disc at a point on its vertical diameter about one-quarter of the way from its lower edge. As the disc was rotated one could observe through the sighting-tube a number of white posts, which were driven into the ground on the circumference of a circle of 50 yards radius, the sighting-tube being at the centre. The pegs were 10 degrees apart, and the zero reading was given when the central post, the source of sound, and the sighting tube were in line.

Bearing (degrees).	Deflection (divisions).	Bearing (degrees).	Deflection (divisions).
90	45	0	43
80	31·5	−10	16
70	17	−20	Min. 2
60	5·5	−30	10
52	Min. 1·4	−37	Max. 14·5
50	1·5	−40	12
40	12·5	−50	2
37	Max. 14·5	−51	Min. 2
30	10	−60	6
20	2	−70	18·5
19	Min. 2·0		
10	20	−80	32
0	43	−90	45

If we plot bearing and deflection, which for faint sounds measures the amplitude of the vibration, a curve of the form shown in fig. 21 is obtained.

It is thus seen that the diffraction gives a central maximum equal in intensity to the sound which passes the edge of the disc, and this is surrounded by a ring maximum.

A variant of this experiment was performed in which the disc was set to give different angles of incidence for the sound, and the microphone was moved along a horizontal diameter until a maximum effect was given. One thus obtains an image of the source for each angle of incidence, and the distance of this image from the centre of the disc gradually increases as the angle of incidence is increased.

The image, however, becomes ill-defined for angles of incidence exceeding 20 degrees, and the tendency is then to obtain a train of maxima of nearly equal intensity when the microphone moves from one edge of the disc to the other.

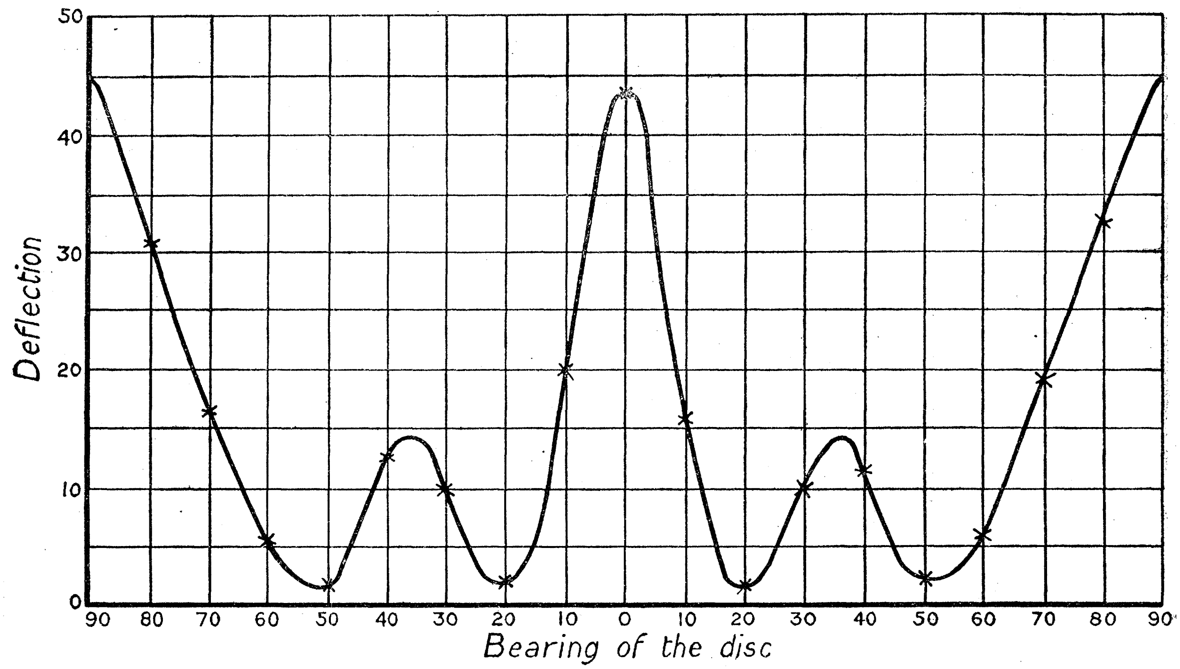

Fig. 21.

The above illustrations give some indication of the manner in which the microphone can be applied to the investigation of acoustical problems. Many of the measurements described in this paper were made in a locality where a certain amount of noise was constantly occurring, but which the microphone, being highly tuned, failed to record. Tuned reception for sound has all the advantages of tuned reception in "wireless" in distinguishing and magnifying faint signals.

A distinct limitation of this microphone is its restriction to the measurement of low-frequency sounds, but it is hoped to devise a microphone of the Hot-Wire type sufficiently sensitive to deal with speech frequencies.

§ 10. *Summary.*

A new form of Selective Hot-Wire Microphone is described, consisting of an electrically heated grid of fine platinum wire placed in the neck of a Helmholtz resonator. The effect of a sound having the same frequency as that natural to the resonator itself is to produce an oscillatory motion of the air in the neck, which in turn causes a change in resistance of the platinum wire grid. The total resistance change comprises a steady fall

in resistance due to an average cooling of the grid, and a periodic change due to the to-and-fro motion of the air. Two methods of using the microphone are described :—

(i) A Bridge method, depending on the steady drop in resistance ; and
(ii) An Amplifier method which makes use of the periodic resistance changes.

Curves are given showing the sharpness of resonance as measured by the Bridge method.

The various factors affecting the sensitivity of the microphone are discussed. The most important, from a practical point of view, is the variation of the sensitivity with the heating current of the grid. It is found by experiment that the sensitivity always increases as the heating current is increased. In the case of the Bridge method, it is found that the steady resistance change produced by a sound of given intensity is a linear function of the temperature of the grid above its surroundings measured on the platinum scale.

The results of experiments on the cooling of the grid by low velocity air-currents are described. From these results it is deduced that the principal resistance changes to be expected when the grid is cooled by an oscillatory air-currents are :—

(1) A steady drop due to an average cooling ;
(2) A periodic resistance change at the same frequency as that of the sound ; and
(3) A periodic resistance change of frequency twice that of the sound.

All these effects are found in practice.

Further deductions are that the steady change of resistance is proportional to the *intensity* of the sound, while the periodic resistance change in (2) is proportional to the *amplitude*. These conclusions are confirmed by experiment.

A description is given of the effect to be observed when the microphone is tilted at various angles, and the observed facts are compared with what would be expected from the results of experiments with steady air-currents.

Finally, an account is given of some experiments which exemplify the use of the Hot-Wire Microphone for observing the intensity and distribution of sound.

The work described in this paper forms part of an investigation commenced in the Munitions Inventions Department, and continued later at the Signals Experimental Establishment, Woolwich.

In conclusion, the authors wish to express their indebtedness to the Chief Experimental Officer of this Establishment for the interest which he has taken in the progress of the work, and for the facilities which they have received for carrying out experiments.