SOME INVESTIGATIONS INTO THE VELOCITY OF SOUND AT ULTRA-SONIC FREQUENCIES USING QUARTZ OSCILLATORS

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Abstract

The velocity of sound at ultra-sonic frequencies is measured over a frequency range from 40 to 216 kilocycles per second using quartz crystals as sound oscillators. The emitted sound is reflected back upon the source and as its phase changes the plate current of the quartz oscillator goes through a series of maximum values. The distance moved by the sound reflector between these maxima is a half wave-length of the emitted sound.

The velocity is obtained in air free from CO_2 at three values of the relative humidity, dry, 45 percent relative humidity at 20°C, and in air saturated with water vapor at 20°C.

The velocity is found to change with the distance from the source, becoming smaller as the distance becomes greater. This was particularly noticeable at 42 kilocycles.

At a distance of 45 centimeters, all values except those below 60 kilocycles become within 0.03 percent of an asymptotic value of 331.60 meters per second.

The velocity is found to depend upon the number of wave-lengths from the source.

The effect of humidity upon the velocity is found to be expressed by

$$V_H = V_0 + 0.14H$$

where V_0 is the velocity in dry air at 20°C and V_H is the velocity at any relative humidity "H" at 20°C.

THE scope of the present work was intended to include the measurement of sound velocities from about a frequency of 40 kc up to 2000 kc in several ordinary gases. Actually the investigation up to the present has been limited to measurements in air for other problems came by the way which needed solution before the research could be pushed further. As a start it was decided to check the work which had been done in air by Professor Pierce,[1] in particular, to see if the considerable increase in velocity reported by Professor Pierce for the region about 40 kc could be checked. This turned out to be somewhat difficult, and the problem has become a study of the velocity in air in the frequency range from 40 to 216 kilocycles and at various distances from the source. The effect of humidity upon velocity has been studied experimentally. The results seem to shed some light upon the reported increase in sound velocity at 40 kilocycles and indicated that the whole phenomenon is extremely complicated and interesting.

In the following experiments, the control and measurement of four variables constituted the major part of the problem in hand. These were, the

[1] G. W. Pierce, Proc. Am. Acad. of Arts and Sciences **60**, No. 5 (1925).

wave-length of the emitted sound; the frequency of this sound; the temperature at which the measurements were made; and finally, the constitution of the medium through which the waves were propagated.

As in Professor Pierce's paper the sound was produced by means of quartz crystals, the use of which has by this time become quite common as frequency-control devices. If quartz crystals are used in conjunction with a vacuum tube circuit of the proper sort, the circuit will oscillate electrically with a frequency determined by one of the natural mechanical periods of vibration of the crystal. Such a circuit based on Figs. 5 and 6 of Professor Pierce's paper is shown in the accompanying diagram, Fig. 1, together with an amplifier.

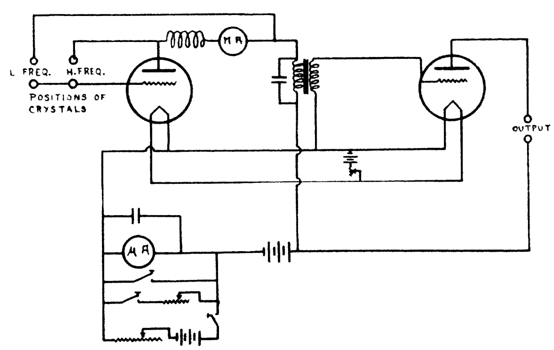

Fig. 1. The oscillating circuit together with the audiofrequency amplifier and microammeter, showing shunting and bucking arrangement for the microammeter.

The Measurement of Wave-length

Simultaneously the mechanical motion of the crystal produces longitudinal elastic waves of the same frequency in the medium in which it is situated. To measure the wave-length of such a disturbance a very convenient method is available. It has been found by Professor Pierce that if a solid reflector be moved in a direction perpendicular to the sound emitting face of the crystal so that the sound is reflected back to the crystal face, small changes occur in the plate current of the circuit shown. This current goes through a series of maximum and mimimum values as the reflector is moved. The distance between successive maximum values of the current represents a half wave-length of the emitted sound. Since this change is small in comparison with the steady plate current, it may be detected more readily by means of a microammeter which is made to read zero for the normal plate current by means of a local bucking battery and a proper variable resistance. It was also convenient to have a variable shunt and short-circuiting switch, as indicated in the diagram, Fig. 1. Such an arrangement made it possible to use current variations of as little as four microamperes to determine the wave-length.

The position of the reflector was obtained by means of a precision screw of half millimeter pitch provided with a micrometer head divided into 100 parts so that one division on the dial indicates a motion of 0.005 millimeters. This screw was calibrated under actual working conditions by checking against a good standard meter for every five centimeters of length.

The Measurement and Control of Frequency

The frequency of the sound source was measured in terms of a standard crystal which was kept in a fixed position during any set of measurements. This standard was calibrated directly from the clock at the Harvard Observatory by means of the method of coincidences described by Professor Pierce.[2] Its frequency was known at any one temperature and its temperature correction was also known. The value of this frequency was close to 421 kilocycles. At any temperature its frequency was known to about three parts in four hundred thousand.

All the crystals used in this experiment had been cut by Professor Pierce and had been ground by him so that they had a frequency such that some harmonic would produce an audible beat with the 421 kc standard. The frequency of this audible beat with the standard was measured on a calibrated

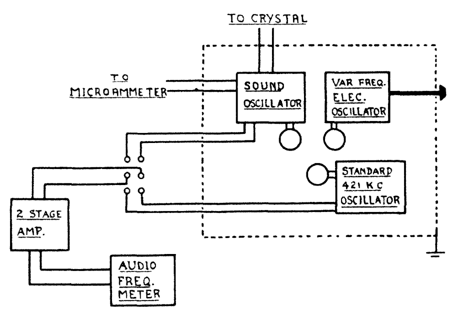

Fig. 2. Relative position of the piezoelectric sound oscillator and the oscillators and amplifiers used in determining the frequency of the sound.

audiofrequency meter and could be determined within two or three cyles per second giving an accuracy better than one part in one hundred thousand in the frequency of the sound source. The harmonic was identified by means of a wave meter.

The control of the frequency offered no difficulty, as the crystals once oscillating continued at constant frequency so long as they were undisturbed. The frequency measured at the beginning and at the end of each run was never significantly different. The disposition of the oscillators is shown in Fig. 2.

The Measurement and Control of Temperature

The effect of temperature on velocity was computed from the known relation between velocity and temperature. If one wishes an accuracy of 0.01 percent or better, then the temperature must be measured within 0.05°C.

The temperature was measured by means of a mercury in glass thermometer (No. 6466) divided directly into tenths of degrees centigrade which

[2] G. W. Pierce, Proc. Am. Acad. of Arts and Sciences **63**, No. 1 (1928).

could be read to 0.02°C. This was placed within 10 centimeters of the vibrating air column. Precaution was taken to have it at the same vertical height as the crystal, so that any vertical temperature gradient would be avoided.

This thermometer was compared with a German Standard thermometer (P.T.R. 42547) kept in the Jefferson Coolidge Chemical Laboratory. The thermometer was carefully calibrated against this throughout the range over which it was used. This range was only five degrees in length, viz. 18.00°C. to 23.00°C. Corrections have been applied as they were found in the calibration.

The problem of keeping the air at nearly constant temperature forced the apparatus to be arranged in a manner such that the sound chamber was in a separate room from the operator. This room was only entered when crystals were changed, and its temperature altered very little since the room was below ground level and had no windows and no heating system. During the period over which a single set of measurements were taken, say half an hour, the observed reading on the thermometer seldom changed perceptibly. This thermometer was read from the operator's room by means of a short focus telescope. Since the room was undisturbed and the sound container was metal, it was believed that this observed value indicated accurately the temperature of the enclosed air. This is further substantiated by the fact that on several occasions when air inside was thoroughly stirred, no variation of the reading took place, nor did any occur when the thermometer was forced more deeply into the container.

The Measurement and Control of Humidity

Professor Pierce had been lead to the conclusion that change in humidity produced little effect upon the velocity of sound at these frequencies, but since this is not true at lower frequencies, it was thought advisable to control this factor if possible.

The method used for the determination of humidity was that suggested in International Critical Tables[3] depending upon the constancy of the vapor pressure over saturated solutions of various salts. For example, if excess KNO_2 be dissolved in distilled water, the vapor pressure is such that the relative humidity at 20°C is 45 percent. Such a solution was placed inside the sound box while measurements were taken. A hair hygrometer placed in the sound box observed through a window served as an indicator for change in humidity.

When dry air was required the air was pumped through $CaCl_2$ and then over fused sodium hydroxide which also removed CO_2. To conserve drying agents and facilitate the drying, the intake of the blower was connected to the sound chamber and thus the same air was passed many times over the drying reagents. Beside this a dish containing P_2O_5 was placed in the container. When air saturated with water vapor was needed, a bubbler was put in series with the pump, and an open dish of distilled water replaced the P_2O_5. The CO_2 was removed by bubbling the air through a solution of NaOH.

[3] International Critical Tables Vol. 1, p. 67

Attention may be called here to the fact that while all results have been reduced to values at 0°C, the amount of moisture present is still referred to 20°C.

Alignment of Crystal

In most of the work the crystal was mounted on a platform rigidly attached to the gas container and was made level when the apparatus was in position. Later, a means of tipping the crystal was devised. It was found that the error produced by lack of alignment was small, for when the crystal was deliberately tipped, the change in length of a given number of half-waves was less than would have been predicted by the use of the cosine of the angle. The crystal was set by tipping it up and down until a maximum reaction was obtained with the reflector at a great distance away. In this manner the crystal could be lined within half a degree.

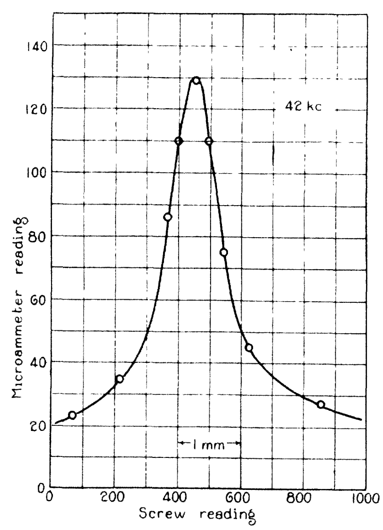

Fig. 3. A typical current peak a short distance from the source at 42 kilocycles per second.

Experimental Method for Location of Nodal Positions

While it was possible to measure frequency, temperature, and humidity quite as indicated in the preceding pages, the measurment of the wavelength was a question which turned out to be much more difficult in several respects.

If the readings of the microammeter be plotted against the distance as read by the screw, a series of maxima appear. These maxima will be referred to as "peaks" and the length of a half wave as the distance between two successive peaks.

To obtain the position of the peak with the greatest accuracy, it was impossible to set on it by moving the reflector to the position where the meter gave its largest reading, for it was found that in all cases the top of the peak was flat over a number of scale divisions. This is evident from Fig. 3. To avoid this, readings on either side of the peak were taken (e.g. when the meter reads "110"). At this point the motion of the needle was great for a small displacement of the piston. Thus the reading can be made with greater accuracy. The mean position of the reflector on the two sides of the peak was taken as its true position.

Back lash existed, but its effect was avoided by taking readings travelling first in one direction and then in the opposite. This also avoided trouble due to change in back lash from point to point. The calibration of the precision screw was also carried out in this manner. Even without any back lash the position of the peak in space is different when the reflector is being moved out from that when the movement of the reflector is in the opposite direction.

Hence a mean position of the reflector going in and out has been taken in every case. The procedure is illustrated by the following readings taken to determine the position of the maximum.

1. Reflector moving in
   57707 meter reading increasing
   57665 meter reading decreasing
   57686 average
2. Reflector moving out
   57732 meter reading increasing
   57764 meter reading decreasing
   57748 average
3. Actual position
   57686
   57748
   57717 average
4. Difference between two indicated positions
   57748
   57686
   62 divisions
5. Known back lash 48 divisions
6. Shift of position independent of back lash is 14 divisions.

The shift in "6" is not constant, but by using the above method the length of an interval could be determined consistently, with an accuracy dependent upon the frequency of the sound emitter, but seldom with an error of more than ± 3 divisions on the graduated wheel and usually not more than ± 1.

Possible Percentage Error

Having dealt with the control and measurement of the four variables concerned, it is interesting to note the accuracy with which sound velocities might be obtained under such conditions. Let us suppose 50 centimeters of the screw could be utilised for measuring purposes and that the maximum points could be located to two divisions on the wheel. The percentage error thus introduced would be 0.004 percent. The frequency can be found to better than one part in thirty thousand and hence introduces a possible error less than 0.003 percent. The temperature can be measured to 0.02°C and thus introduces an error of four parts in one hundred thousand or 0.004 percent. Since the air is kept at a fixed humidity the accumulated percentage error may amount to as much as 0.01 percent.

The work had not progressed very far before it was observed that the number of variables concerned had been underestimated, for with all possible precautions results did not check each other unless taken at exactly the same distance from the vibrating crystal.

Precautionary Experiments to Prove Reality of Change in Wave-length

It must be noted here, that the word "velocity" is used to denote the product of the measured frequency and distance moved by the reflector between alternate "peaks" of current in the plate current of the oscillator. The words "half wave-length" will be used to denote the distance moved by the reflector between peaks.

It was found that velocities computed from measured intervals close to the crystal showed a marked increase in magnitude. While this seems to be true to some extent at all frequencies, the effect is much more marked in the case of 40 kc and most of the experimenting has been done using this frequency.

In order to give an account of these experiments, it will be necessary to describe briefly the apparatus in use at this time. This consisted of a brass box containing two compartments connected by a rectangular opening. In one of these compartments the crystals were arranged on a movable slide in such a way that any crystal which was to be used could be moved to a position where it could radiate sound into the adjoining chamber. This has been designated "the sound chamber." The whole box was mounted on one end of a lathe bed which supported the measuring screw. As a result only a little more than half of the total length could be used for measuring. The reflector was on the end of a piece of one-inch brass tubing which passed through a snug-fitting gland in the end of the sound chamber remote from the crystal. This made a system that was tight enough to prevent very much diffusion of gas from the outside.

The aperture which led from the crystal chamber was larger than the largest crystal face, and hence all radiation from the face entered the sound chamber. The latter had a square cross section 18 centimeters to a side and had a length of about 35 centimeters. The actual interior space was really smaller than this due to the padding.

Padding was always necessary, but no change in it altered the fact that high results were obtained close to the crystal face. The size of the reflector was altered with no results. A felt tunnel was constructed of the same size as the reflector, but this produced no change. A felt pad of cross section equal to that of the sound chamber was fastened to the back of the reflector, and hence the length of the box changed with each setting. Thus any resonant effect due to the fixed size of the sound chamber should be discovered. This also failed to produce any decrease in the wave-length. Two crystals having approximately the same frequency but with different areas of radiating faces were available, both of which produced similar high results.

It was thought that the sagging of the reflector due to its own weight might introduce errors. This would be specially true when the reflection was near the crystal face at which time it hung far out from its support. With this in mind, one of the crystals was set up outside the chamber and the length of groups of waves measured in a region quite close to its face. Then the crystal was moved closer to the lathe bed and the readings repeated. The same increase was noted, but this time the piston hung only half the distance over its support. Thus it was decided that there was no measureable error due to the sagging of the reflector.

At the same time the effect of placing objects in the vicinity of the vibrating column was tried. It was found that even when solid objects were placed but a few centimeters below the direct path of the sound, no noticeable change was made in the position of a particular peak which had been located previously.

Rough measurements made at this time indicated that for all the frequencies used an increase in wave-length could be noted close to the source with or without the container.

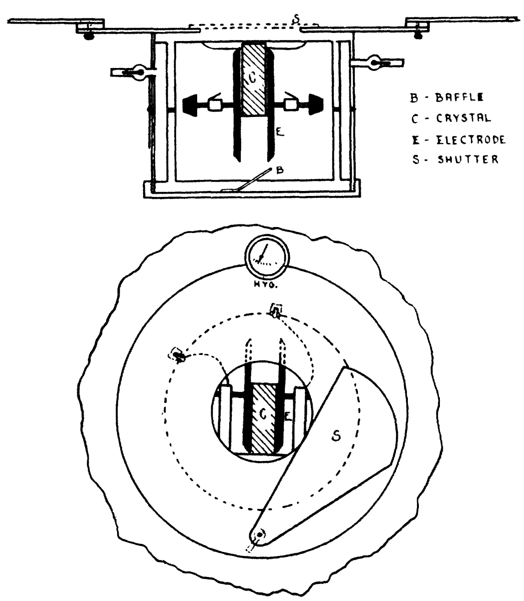

Fig. 4. Two views of the crystal holder and crystal chamber. a. Horizontal section of crystal and holder. b. Elevation of crystal and electrodes as viewed from within sound chamber.

Description of Apparatus

As a result of these experiments, it was concluded that the inequalities of the distances between peaks were real and that sound velocity determinations carried out in this way gave values apparently different for different distances from the source and suggested measurements at greater distances from the source. This made it necessary to reconstruct the chamber of the apparatus. The revised disposition of this apparatus has been partly described in the general discussion, but since the revised arrangement has been used for all measurements recorded here, a fuller description is warranted. The revised arrangement consisted of a sound box long enough to permit the use of the full length of the measuring screw, and of sufficient diameter to permit its use without padding the walls. The actual dimensions were 60 centimeters in length and 45 centimeters in diameter. The crystal holder had circular electrodes whose distance apart could be changed easily. The crystal con-

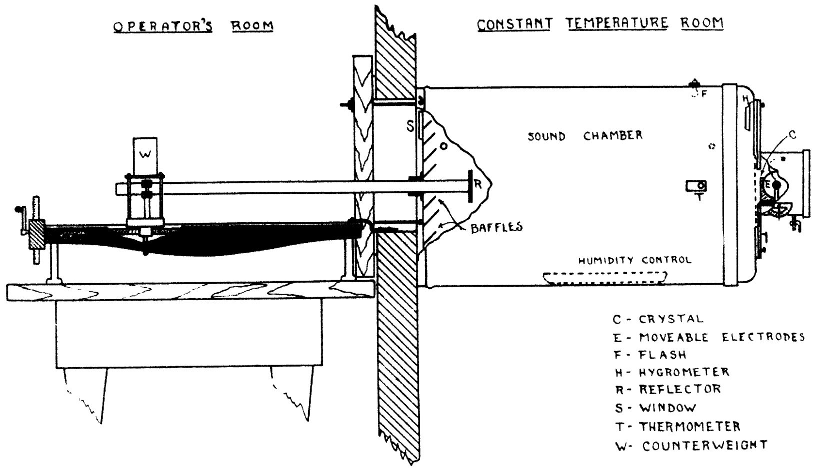

Fig. 5. A general view of the position of the precision screw and sound chamber.

tainer was arranged to permit easy access without opening up the whole sound chamber to the outside air. This was attained by having a slide that could be used to cover the aperture between the crystal chamber and sound box when crystals were to be changed. This slide is shown in the diagram, Fig. 4 by a dotted line. Since the whole container was located in a separate room, the temperature stayed very constant as mentioned.

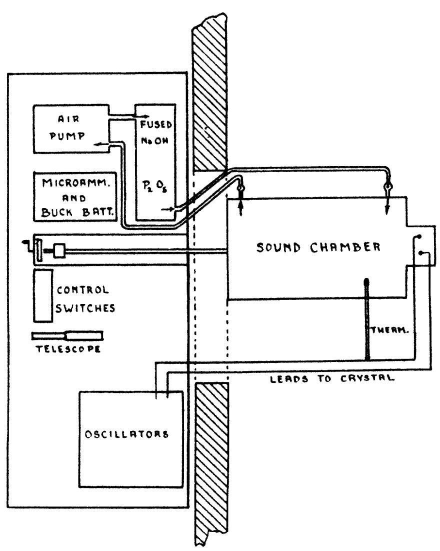

Fig. 6. A plan of all the apparatus.

An attempt was made to shield the lead which went from the piezo-oscillator circuit to the crystal, but the crystals refused to oscillate. The leads were kept apart for best results. A complete diagram of the apparatus is appended in Fig. 5 and the disposition of the apparatus is shown in Fig. 6.

Experimental Method

The procedure for taking data was as follows. The sound oscillator was started, and the switch putting the bucking battery in circuit was closed. This was allowed to run for at least half an hour so that the change in voltage of the bucking battery would not cause the needle of the microammeter to drift. Immediately before the reflector was moved, the temperature of the air was taken, and the beat note with the standard crystal was recorded. Then the position of peaks for equal intervals of from 10 to 50 half waves were recorded as rapidly as could be done conveniently. This completed, the temperature and frequency were taken again, and averaged with the values taken before the run.

Method of Using Data

The fact that the wave-length changes with position makes it necessary to alter the method of averaging employed previously. The method used by

Table I.

Freq. (kc/sec.)	Veloc. (m/sec.)	No. of runs	Distance from source (cm)	wave-lengths
42	333.24	8	12	15
42	332.14	4	20	25
42	332.12	8	32	40
42	332.07	7	40	50
42	331.75	6	53	65
60	332.17	4	12	20
60	331.94	15	29	50
60	331.82	17	40	70
60	331.73	17	52	90
70	332.34	3	12	24
70	331.63	8	30	60
70	331.92	8	40	80
70	331.63	8	51	105
84	331.94	2	20	50
84	331.63	11	29	75
84	331.76	6	35	85
84	331.72	11	51	125
84	331.77	6	51	125
105	331.79	7	17	53
105	331.62	7	32	100
105	331.73	11	40	125
105	331.61	8	49	150
105	331.65	12	49	150
140	331.82	3	16	65
140	331.67	7	32	130
140	331.75	4	32	130
140	331.63	9	32	130
140	331.60	7	49	200
140	331.67	4	49	200
140	331.60	9	49	200

Professor Pierce[1] assumes the presence of equal intervals, the only difference being the experimental uncertainty of measurements. In the present case this is not true except in a limited region for the two highest frequencies used.

The manner in which the results were finally computed was decided after most of the runs were made. The readings were taken as if Professor Pierce's method were to be followed, but the method actually used is described below.

The average wave-length was taken over a distance which could be measured with an accuracy of better than 0.01 percent (viz., three hundred turns of the screw, or 15 cm). *This gave the mean velocity about a point midway between the ends of this interval.* The number of half wave-lengths used was dictated by convenience so long as the total interval did not greatly exceed three hundred turns of the screw. The average was found merely by taking the difference between the end points and dividing by the number of wave-lengths in the interval. When the waves were equal in length in the interval, the average obtained in this way did not differ significantly from that obtained by Professor Pierce's more elaborate method.

The results have been calculated for the most remote 15 centimeters of the screw, then for the next 15 centimeters, and so forth. The distance from the crystal face in wave-lengths at which the results may be considered as average velocities has been listed in Table I. In most cases the 15 centimeter divisions are only approximate as will be seen upon referring to the table.

The results tabulated in Table II are those computed from readings taken over a distance about 15 centimeters in length at an average distance of 45 centimeters from the source.

TABLE II. *Dry air at 0°C. free from CO_2.*

Freq. (kc/sec.)	No. of runs	Velocity m/sec.	Freq. (kc/sec.)	No. of runs	Velocity m/sec.
140	16	331.60	70	8	331.63
105	20	331.63	60	17	331.73
84	17	331.74	42	6	331.75

If this velocity be assumed constant, the maximum variation from the mean is 0.08 meters which is 0.024 percent and is within the limit of error of the experiment.

Taking the average velocity over the same region, remote from the source I have found the following (Table III) for air free from CO_2 at 45 percent humidity at 20°C.

TABLE III. *Air, free from CO_2 at 45 percent relative humidity at 20°C.*

Freq. (kc/sec.)	No. of runs	Velocity m/sec.	Freq. (kc/sec.)	No. of runs	Velocity m/sec.
140	8	332.20	70	8	332.31
105	7	332.27	60	10	332.16
84	8	332.28	42	5	332.38

With the same conditions as above, we have a maximum deviation from the mean of 0.06 meters which is 0.018 percent, which is also within experimental error.

The values of the velocity in air saturated with moisture are not so consistent due to the fact that the crystals would only oscillate for a few minutes in the moist air and measurements were necessarily hurried. This was more serious at low frequencies where more time was needed to make the measurements. Results are given here (Table IV) for four different frequencies. These results were found for the sections of the sound chamber most remote from the crystal.

TABLE IV. *Water saturated air, free from CO_2 at 20°C.*

Freq. (kc/sec.)	No. of runs	Velocity m/sec.	Freq. (kc/sec.)	No. of runs	Velocity m/sec.
140	14	332.97	84	6	332.86
105	8	333.00	42	4	333.34

The maximum variation here is 0.16 meters which gives 0.05 percent, which is a little worse than the other results. The results in Tables II, III, and IV are plotted in Fig. 7.

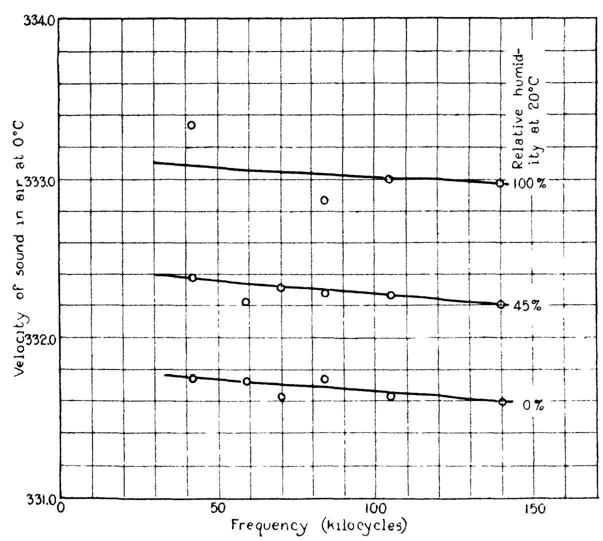

Fig. 7. The velocity of sound in air at 0°C at different frequencies and under different humidity conditions.

By taking the average values at all frequencies for dry, 45 percent humidity, and saturated air we obtain the following velocities in meters per sec.

Dry	45% relative humidity	Wet
331.68	332.27	333.05

These values of the velocity are plotted against the relative humidity at 20°C in Fig. 8. For convenience the actual values of velocity have been reduced to 0°C.

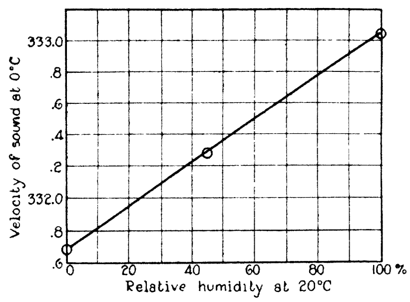

Fig. 8. The relation between the average values of the velocity of sound at all frequencies and the relative humidity at 20°C.

As a result the velocity "V_H" at any relative humidity at 20°C, is related to the velocity "V_0" in dry air at 20°C by the equation.

$$V_H = V_0 + 0.14H$$

where "H" gives the value of the relative humidity (i.e., that fraction of the amount of moisture which would be required to saturate the air at 20°C).

In addition to the values for the velocity in dry air given in Table II, some further values have been obtained using a so-called direct current amplifier which has been built in order to work at points still more remote from the crystal.

The values tabulated below are the average values taken in a region beyond 40 centimeters from the face.

TABLE V.

Freq. kc/sec.	Velocity at 0°C meters/sec.	Freq. kc/sec.	Velocity at 0°C meters/sec.
216	331.66	70	331.56
140	331.64	60	331.63
105	331.61	54	331.87
84	331.61	42	332.00

As in the preceding work, the values for the low frequencies seem high.

VARIATION OF VELOCITY WITH DISTANCE FROM FACE OF CRYSTAL

The fact still remains that the values of this velocity seem to vary with distance from the crystal, and enough data are available to give some idea of how this variation takes place. In Fig. 9 the values of the velocity are plotted against frequency for intervals at different average distances from the source. In Fig. 10, the same values of the velocity are plotted against the average number of wave-lengths from the source, at which the measurements were made.

From the former plot, it will be seen that as the chosen interval becomes more remote from the source the values of the velocity approach more nearly

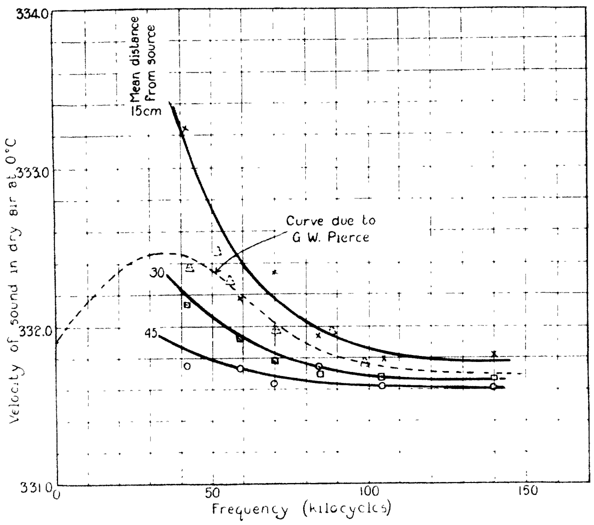

Fig. 9. The relation between the velocity of sound at 0°C and different frequencies to the distance from the sound source at which these measurements were taken.

a common value. The greatest deviations from this common value occur at the lower frequencies.

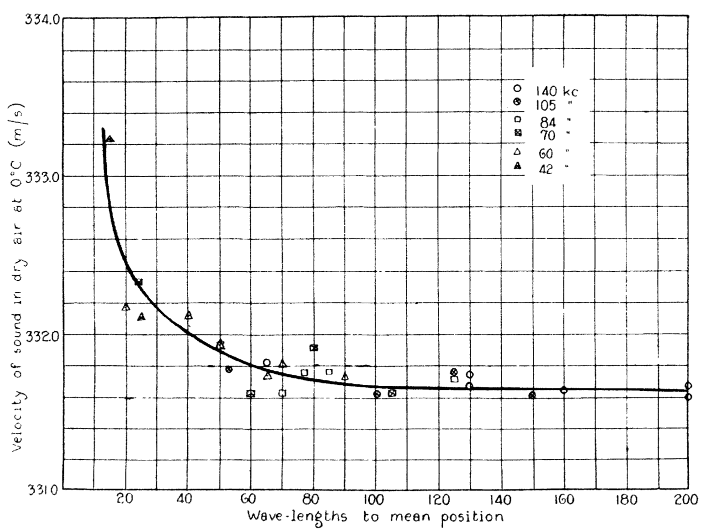

Fig. 10. A curve showing the relation between the velocity of sound, as measured by this method, with the number of wave-lengths from the source, for the frequencies indicated.

It will be seen from Fig. 10 that the size of this deviation depends upon the number of wave-lengths distant from the source at which the measurements are taken.

It will be noted that to obtain the velocity values shown in Fig. 10 it was necessary to make the readings over a considerable distance. For lower frequencies this meant about 40 half waves, while for the frequency of 140 kc this number is of the order of 150 half waves. Hence the closest permissible values at 140 kc will give a mean velocity about 75 wave-lengths away. It will be seen that an increase in velocity in the vicinity of the source would be

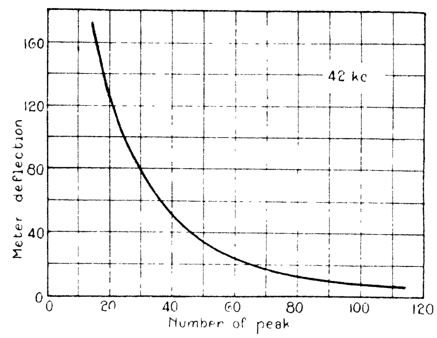

Fig. 11. A plot of the amplitude of 36 consecutive peaks (reading of microammeter against distance) against the number of the peak (starting from the source).

masked in this manner. Thus no real close-up values have been obtained for the higher frequencies. Similar experimental difficulty presents itself at a large number of wave-lengths for the lower frequencies, as the most extreme position at 42 kc was only 80 wave-lengths, and it seems improbable that this is far enough to give the asymptotic value obtained at a great distance.

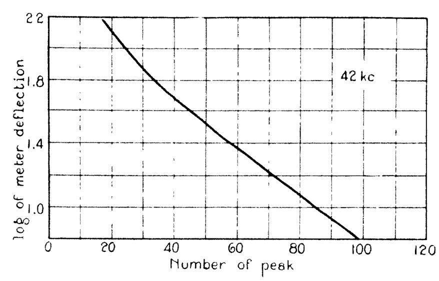

Fig. 12. The logarithm of the deflection plotted in Fig. **11**.

Since the velocity close to the source could be studied better by means of the 42 kc crystal, some extra attention has been bestowed upon this. Starting from a position about fourteen half wave-lengths from the source, the next 36 consecutive peaks were plotted (ie., the reading of the microammeter was plotted against the distance), from this point on, every tenth wave was plotted until the 129th half wave was reached.

From these curves a decrement curve, Fig. 11, was plotted to a different scale and also the logarithm of the microammeter deflection, Fig. 12. The latter was very nearly a straight line except for the first few readings. The decrement was found to be 0.015 per half wave. This is altogether too small to affect the velocity to the extent which is indicated by these experiments.

A graphical examination was made to ascertain the shift in the position of the peak due to this decrement and the effect of the decrement on the position of the peak was found to be negligible. Since the equation of the reaction current was unknown, this was the only available method.

It is worth noting that in addition to the change in wave-length with distance from the source, variations beyond experimental error occur in the separate intervals at the lower frequencies and in extreme cases amount to about 0.5 percent of the length of the interval when this is in the vicinity of the source.

Summary and Discussion of Results

An attempt has been made to obtain the value of the velocity of sound at frequencies from 40 kc to 216 kc under conditions simulating outdoors, but at the same time to have greater control over the variables concerned.

Values have been obtained at eight different frequencies for three humidity conditions and at different distances from the source. An apparent rise in wave-length has been noted for regions close to the source, but which at any given position is greater the lower the frequency. As one recedes from the face of the oscillator, the velocities at various frequencies appear to approach a common value. If the velocity as found for all frequencies be plotted against the mean distance from the source in wave-lengths, some relation appears. A study at 42 kc shows that as the reflector recedes from the crystal, the value of the microammeter deflection (the change in plate current in the oscillator) decreases smoothly with a decrement nearly logarithmic, but too small to affect the length of the interval appreciably.

The method employed here has the advantage over tube methods since there is no tube correction to be considered. With the apparatus used, the diameter was equal to sixty of the longest wave-lengths used. This would correspond to a room about 60 feet in diameter for sound of about 1000 cycles.

While it is quite probable that some trouble arose due to reflections from the walls, it is hoped that at some distance from the source such effects are small. Small variations were noted from day to day which may have been due to this cause. Small temperature changes would cause marked alterations in any disturbance of this sort, as the path of wave reflected from the sides of the sound chamber would be much longer than that of the direct beam.

The rise in velocity near the sound source has been observed before. At Chicago in 1905 T. C. Hebb,[4] working in a large hall with audible sound of wave-length approximately 10 inches, found this same effect. He noted the increase in the wave-length as the source was approached and specifically mentions that it was beyond experimental error. The length of the wave seemed to approach a limit as he reached positions fifty to sixty wave-lengths from the source. A shorter wave-length used seemed to make the trouble less obvious, though it was noted that he was farther from the source to begin

[4] T. C. Hebb, Phys. Rev. **20,** 89 (1905).

with and took a greater number of waves for his average length. No explanation was offered save that he thought that his reflecting mirrors were not large enough for the first wave-length he used. Since the above experiment was similar to the present experiment in many ways, it is interesting to note a similar phenomenon was observed.

The cause of this rise in velocity near the source has not been determined definitely so far, but several possibilities present themselves. Regnault found that velocities near the source were high and assumed that this was due to intensity. This can scarcely be true here as the energy radiated as sound is extremely small, for the input to the crystal oscillator, (exclusive of filament) was less than one-tenth of a watt. Some apparent increase would result from the lack of a plane wave system when a comparatively large reflector is used. However the effect is too large to be altogether accounted for by this argument.

An investigation using two crystals with different faces but having the same frequency indicated that the face of the crystal affects the result when the reflector is close to the face. Furthermore it seems probable from some recent work that in the case of higher frequencies no large rise in velocity takes place. A recent experiment showed that this was true when a 54 kc crystal with a small face was used. It is difficult to study the effect of the shape of the crystal face as they are not available in general with differing faces and the same frequency.

It is difficult to see why the reaction in the microammeter should fall off smoothly when passing through a region which must have an elaborate diffraction pattern, unless the reflector was large enough to average out diffraction effects.

The values of the ratio of the specific heats of air deduced from the velocity at 140 kc which seems to be close to the asymptotic velocity, Fig. 10, is 1.4035. This is in good agreement with the average of the best results today, computed from the velocity of sound at audible frequencies.

The average velocity in dry, CO_2 free, air as computed from the values at six frequencies is 331.68 meters per second. This result is felt to be too high, and if measurements at greater distances from the source could be taken for the lower frequencies, it seems that the results ought to decrease to 331.60 meters per second, as this seems to be the asymptotic value.

It will be noted that if the investigator had been limited to any particular region on the screw the results would have indicated, Fig. 9, a higher value for the velocity especially at the lower frequencies. As the interval over which measurements were taken was moved further from the source this increase in velocity becomes less noticeable. A further examination of the data published by G. W. Pierce[1] was undertaken by Professor Pierce and the author and revealed that these measurements were taken in a region extending from the face of the crystal, out to a point about twenty centimeters distant. This will account for the similarity of the shape of the dotted curve, Fig. 9, with those obtained by the writer. Although the numerical values of the velocity are altered by the fact that no correction was made for humidity, yet the humidity did not change appreciably during the experiments and hence the values lie along a curve similar to those obtained by the present investigator. Notice must be taken that no experimental values have been made below 40 kilocycles per second by this method, either by Professor Pierce or by the writer. The dotted curve, Fig. 9, is merely a reproduction of that published earlier.

The change in the velocity of sound caused by saturation with water vapor at 20°C has been found to be 1.37 meters per second. This agrees very well with values calculated by McAdie[5] and with values computed by the writer, assuming that the change in velocity is due to change in density only. Some work on this subject at audio frequencies has been done by Barss and Bastille,[6] but their results gave a change of only 0.57 meters per second.

An examination of Professor Pierce's note-book by Mr. W. J. Cahill has resulted in showing that at that time there was evidence of a change in velocity with humidity which was overlooked. This has been affirmed by Professor Pierce.

It may be added here that this work was done in three parts several months having elapsed between each set, and that the results check well. In one of these intervals the mounting of the standard was changed and recalibrated.

The following conclusions have been reached. The increase in apparent velocity at frequencies around 40 kc grows smaller as the measurements are taken in regions more remote from the source, and, the velocity in this range of frequencies does change with the humidity.

These experiments have been carried out in the Cruft Laboratory under the direction of Professor G. W. Pierce. Further experiments are now under way in this laboratory by the aid of which it is hoped that many of the present difficulties may be cleared up.

[5] McAdie, Annals of the Observatory of Harvard College **86**, 107 (1923).

[6] Barss and Bastille, Jour. of Math. and Phys. M.I.T. **2**, 210 (1923).

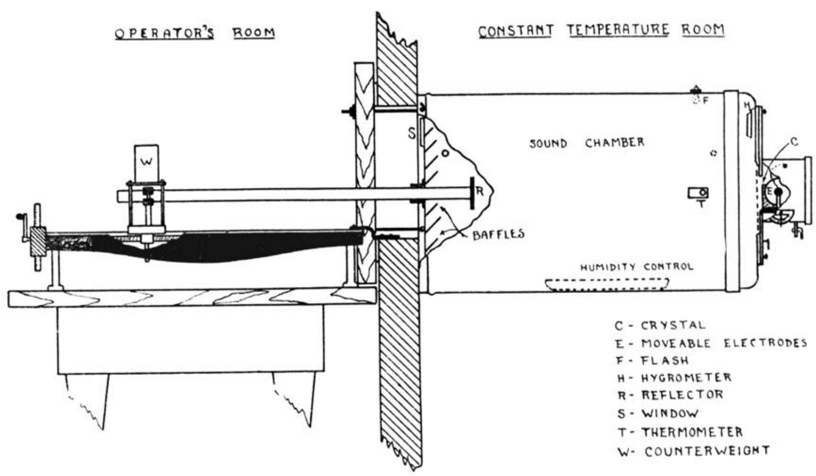

Fig. 5. A general view of the position of the precision screw and sound chamber.