CONTENTS.

SUPERSONIC VELOCITY IN GASES AND VAPOURS.

PART I. ABERRATIONS OF SUPERSONIC INTERFEROMETERS IN GASES.

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INTRODUCTION.

Of the various methods used for measuring the specific heats of gases and vapours, the indirect determination from the velocity of sound, is probably comparatively simple and hence is in extensive use. According to the well-known Laplace equation the square of the velocity of sound in a fluid is equal to $\gamma RT/M$ where γ is the ratio of specific heats at constant pressures C_p, and constant volume C_v, and M is the molecular weight. An equation of state should be available in order to apply a correction for the deviation from the ideal gas state and also for calculating the difference between C_p and C_v.

The velocity of sound is usually measured by the Kundt's dust figures in a tube filled with the gas or vapour. This method has been considerably improved upon in recent years by the use of thermionic valve circuits and telephones instead of the hand operated rod, to produce the vibrations. Other methods developed more or less on the same lines, depend on the resonance of a tube when its length is varied by a movable piston so that its length is an integral number of half wave-lengths at known frequency, or the frequency is varied until resonance is obtained for a given length of the tube. The former has been used by Partington and Shilling, and the latter by Thiesen (*Ann. Phys.*, 1908, **25**, 506), Gruneisen and Markel (*Ibid.*, 1921, **66**, 344) and recently by Keesom and his co-workers at low temperatures.

In all of the above methods, the velocity measured depends on the diameter of the tube. The correction to be applied is given by the Helmholtz-Kirchoff formula $V' = V[1 - c/d\ \sqrt{\pi f}\,]$ where V' is the apparent velocity in a tube of diameter d, V is the true velocity, f is the frequency and c is a factor dependent mainly on the viscosity of the gas and the conductivity of the tube. Very discordant opinions exist as to the method of applying the corrections. [*Cf.* Partington and Shilling (*Phil. Mag.*, 1928, **6**, 920) and Cornish and Eastman (*Phys. Rev.*, 1929, **33**, 258).] In order to diminish the magnitude of correction, apparatus of considerable size had to be used.

G. W. Pierce (*Proc. Amer. Acad. Arts Sci.*, 1925, **60**, 271) measured the velocity of sound in air and carbon dioxide by the method of stationary waves produced by piezoelectric quartz crystals of small size and power, the emitted waves being made to strike a reflector, 9 cm. × 12 cm., fairly close to the source, the whole being kept in a cotton-lined box, 18 × 18 × 35 cm. The position of the reflector could be adjusted by a micrometer screw. By connecting the oscillator to the grid and the filament of a thermionic valve, the oscillator itself could be made to act as a detector of nodal planes. When the position of the reflector was an integral multiple of half wave-lengths from the crystal face, stationary sound waves were formed and the intervening gas acted as a resonator absorbing energy from the oscillating crystal. The potential of this decreased and caused the anode current to increase. The distance between successive positions of the reflector at which the anode current was maximum, was equal to a half wave-length.

Pierce actually recorded values for 20 half wave-lengths and from a sample set of observations given, these intervals varied as much as 2% among themselves, although the setting of the individual peaks was within 0.1%. By taking the weighted mean of a large number of observations an accuracy as high as 1 in 30,000 was claimed for the velocity of sound in air.

Among the results, Pierce detected a slight change of velocity with frequency for air and carbon dioxide and a negligible effect of moisture on the velocity of sound in air. It is interesting to note that the possible change due to moisture is of the same order of magnitude, *viz.*, 0.05% as that ascribed by Pierce to the walls of the chamber with and without cotton padding, the dimensions of the chamber being more than 25 times the longest wave-length tried.

While investigating the alcohol-ether equilibrium (*This Journal*, 1926, **9A**, 99) attention was drawn by Jatkar and Watson to the discordant data available for the specific heats of the vapours of these substances. A redetermination appeared desirable and consideration of possible methods led to the conclusion that the method of Pierce (*loc. cit.*) involving the measurement of the velocity of sound at supersonic frequencies, would be the most suitable. The necessary apparatus was small and could be heated as a whole to any desired temperature while the high accuracy claimed by Pierce appeared to be a decided advantage over other methods involving the velocity of sound.

A quartz crystal was accordingly mounted in a jacketed brass tube 3.5 cm. in diameter fitted with a plunger, the position of which could be accurately measured. The crystal was then caused to oscillate by means of an appropriate valve circuit and observations made of the variations in anode current with movement of the plunger. The anode current should be a maximum at resonance and consequently a maximum should be found whenever the plunger is at a node of the standing wave system formed in the tube. It was at once found, however, that although sharply defined peaks were observed, the distance between consecutive maxima was by no means constant and there were many other irregularities. Repetition of an experiment gave identical values but these were useless for accurate wave-length determination. The effect was different with different gases; carbon dioxide gave fairly uniform results, air occupied an intermediate position and the curves of other vapours were so irregular that it was almost impossible to count the waves. [*Cf.* Jatkar and Watson (*Proc. Ind. Sci. Congress,* 1929).]

HISTORICAL.

Numerous papers on Supersonics have appeared since the early report of the author. W. A. Pielemeier (*Phys. Rev.,* 1929, **34**, 1184) published an account of work carried out to test the accuracy of the Pierce interferometer for velocity and absorption measurements. Using a reflector slightly larger than the top of the crystal which radiated sound waves, he observed more irregularities in wave-length than those obtained by Pierce. The curves obtained by plotting galvanometer deflections and positions of reflector showed:—

(1) Multiple reflections taking place at the movable reflector and the crystal surfaces.

(2) The rise to the maximum was more gentle than the drop to the minimum and the type of such asymmetry changed with increasing distances of the reflector.

(3) The deflection peaks were not uniformly spaced although they were sharp to within 1/200 mm.

(4) Sudden changes in the decrement of the maxima occurred.

These observations were construed by Pielemeier to mean a variable velocity of sound with frequency, due to absorption by gas. The precision in the value of wave velocity was considerably diminished owing to the above causes.

Reid (*Phys. Rev.,* 1930, **35**, No. 7, 814), working under Pierce, has published a revision of data and his work does not support the frequency variation of velocity. The previous positive results were due to the fact that the apparent velocity varied with the distance from the source especially at low frequencies and when near the crystal. He further found that saturated air at 20° C. changed its velocity by 1.37 meters, agreeing with the assumption of change of velocity due to change in density. He further reported an unequal spacing of maxima, what might be termed an 'acoustic back lash', of 0.48 mm. apparently at a frequency of 42 k.c. per sec., while Pielemeier finds an acoustic back lash six wave-lengths from the crystal to be less than 0.01 mm. at $\lambda = 0.0282$ mm. (1219 k.c.).

Hubbard in a letter to the editor (*Phys. Rev.*, 1930, **36**, 1699) reports that he could not detect any change of velocity with intensity as found by Pielemeier or with the length of the path as reported by Reid (*loc. cit.*) at frequencies of 218–476 k.c. per sec.

Grossman (*Phys. Z.*, 1934, **35**, 83–88) found the intervals between the positions of the reflector for maximum reaction on the sender, are not always exactly equal to a half wave-length, but show deviations which depend on the distance between sender and reflector. Neglect of these deviations in a determination of velocity leads to error.

Grabau (*Jour. Acoust. Soc. Amer.*, 1933, **5**, 1) found that irregularities in the wave system varied with frequency as well as with the diameter of the source and reflector and that they vanish at relatively large distances from the source. The values of velocity then show no variation with frequency. He believes that the phenomena of irregular spacing is associated with changing phase of waves within the central diffraction maximum, as the largest reflector is too small to intercept the secondary maxima away from the central diffraction maxima. This conclusion is also arrived at by a detailed examination of the resonance curves by the author.

Kaye and Sherrat (*Proc. Roy. Soc.*, 1933, **141**, 123) have used a narrow tube for measurement of sound velocity at low frequencies in air and other gases. A detailed reference to this work will be made in a subsequent paper.

Recently Eucken and Becker (*Z. Phys. Chem.*, 1934, Abt. B., **27**, 219) found that at low frequencies disturbances through reflection of the long sound waves on the walls of the vessel take place. This led to the sound interference at the transmitter and the galvanometer showed a maximum when no nodes of sound waves were to be expected. These disturbances could be generally removed by using a system of suitable screens which is composed of conical funnels placed one on another and whose action consisted in the perfect absorption of all the sound waves which occur on the sides of the walls. Experiments on similar lines conducted by the present author, produced startling results which will be described later.

J. Zühlke recorded acoustic interferometer readings by a photographic method [*Ann. Physik,* 1934, (5) **21**, 667], which is much more complicated than the very simple one described by the present author.

Norton (*Jour. Acoust. Soc. Amer.*, 1935, 7, 16) found it necessary to make measurements at 10 $\lambda/2$ distance from the source corresponding to the avoidance of the Fresnel region in the optical case and to choose tube diameters properly with respect to the wavelength to avoid plane diffraction.

Pielemeier (*Ibid.*, 1935, **8**, 37) has presented further evidence that supersonic waves in air have a velocity which depends on their intensity and that this velocity approaches the limiting value $(\gamma P/\rho)^{\frac{1}{2}}$ at comparatively low intensities.

None of the above explanations fit the observations of the author. Large numbers of experiments have been made to find out the various factors contributing to the complexity of the wave form in various gases and vapours. In the present paper, the author has presented the earlier results obtained with air at 50 and 95 kilocycles under different conditions.

The results given in this paper are a sample set of observations made by the author more than ten years ago. The title of this paper is based upon the suggestion recently made by W. T. Richards (*Jour. Applied Physics*, 1938, **9**, 298) that a collective work entitled Aberrations of Sonic Interferometers would have a useful place in acoustical literature. At one time the complexity of the 'wave form' was thought to be connected with the complexity of the molecules due to a normal velocity depending upon the 'zero frequency' heat capacity and a series dispersion of velocities depending upon the failure of the several vibrational energies in the molecule to follow the rapidly changing translational energy. But the further simplification in the wave form obtained by suitable midifications of the apparatus, shows that the 'satellites' are due to spurious reactions on the quartz oscillator by the reflection of the subsidiary beams of sound radiated by the crystal and also that of the main beam in which both change of phase and intensity occur.

EXPERIMENTAL.

1. Apparatus.

(*a*) *Valve Circuit*.—The general arrangement of the apparatus is shown in Fig. 1. The crystal-valve system was of the usual type with a tuned anode circuit, the crystal being connected between grid G and filament E. The inductance L_1 was selected so that oscillations ceased at a point near the maximum setting of the 0.0005 μF tuning condenser C_1. By reducing the capacity of this condenser the amplitude of oscillation could be diminished. The same effect could be obtained by means of the variable grid leak but the former method was found preferable. Only 40 volts high tension were used as results were better when the oscillations were weak. The steady anode current was balanced out by the resistance R_2 and was indicated by the galvanometer M_1 and by the mirror galvanometer M, the sensitivity of which was controlled by the potentiometer S_2.

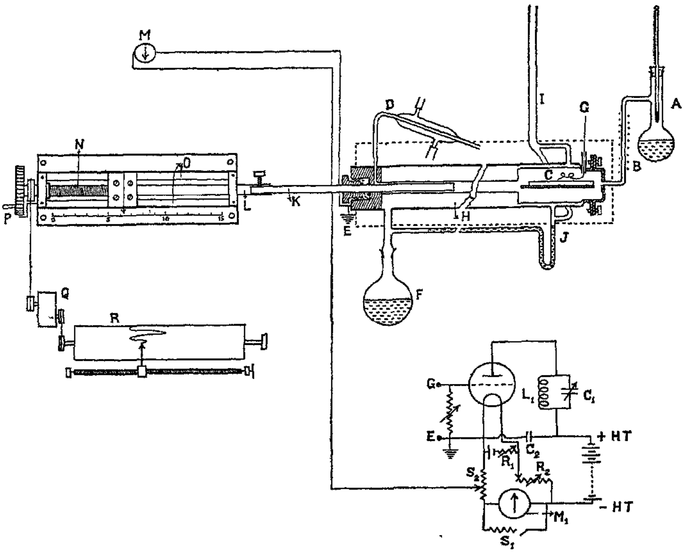

Fig. 1.

(*b*) *Tubes and Reflectors.*—The tube in which the oscillations were excited was made of brass and had double walls, the space between which was used as a heating jacket. A constant boiling liquid was boiled in F, condensed by the reflux condenser I and returned to the flask through the trap J. The whole apparatus was enclosed in an asbestos box to avoid heat losses. In the earlier experiments a single-walled tube, immersed in an electrically heated oil-bath controlled by a thermoregulator, was used. This arrangement was very inconvenient when it became necessary to open the tube to clean or move the crystal. The inner space contained the crystal C, electrical connection to the upper face being made through an insulator of pyrex tube cemented to the brass casing. The illustration shows the smallest inner tube used. This was 10 mm. in diameter and just fitted the plunger K which was made of glass rod ground true. A metal rod being a good heat conductor was liable to affect the temperature of the gas and it was moreover necessary to apply a somewhat uncertain correction for its total length at higher temperatures. When wider inner tubes were employed, a circular disc slightly smaller than the tube was attached to the end of the plunger. The diameter of the largest tube was 8 cm., length beyond crystal being 30 cm. The plunger passed through a stuffing-box at the end of the tube, but as it was essential for its movement to be very free, the nut could not be tightened sufficiently to make the joint quite gas-tight. In all experiments, therefore, a slow stream of gas or vapour was passed through the tube, the position of the outlet shown in the diagram obviating any danger of contamination by leakage. In the case of vapours, the liquid was boiled in the flask A and the vapour superheated by the coil B to avoid the possibility of spray entering the tube.

The plunger was attached to a tube L fastened to a split nut moving in two V guides actuated by screw N with a pitch of 1 mm. This was cut in a lathe and ground true. Readings taken on the graduated head P were found to be accurate to 0.01 mm. The screw assembly and the tube were rigidly mounted on a stout teak plank. Tests were made for errors which might arise from lack of rigidity or sticking of the plunger but none could be found. The screw-head was connected through a reducing gear Q, with the revolving drum R, in such a way that the surface of the drum moved about 1 cm. for each revolution of the screw.

(*c*) *Recording Apparatus.*—In the earlier experiments bromide paper was attached to a drum which was enclosed in a light-tight housing and the wave-form recorded photographically. The drum of the recorder was 8 inches in diameter and was housed in a box 9 in. × 9 in. which was provided with a long horizontal slit. The drum was driven by the screw which worked the piston, through gears. The galvanometer mirror in the anode circuit illuminated the whole of the horizontal slit by a flash lamp worked automatically by every turn of the mm. screw; a ten times magnification was obtained (*cf.* Figs. 2 and 3). The actual wave-lengths were read by means of a diagonal scale, wherever the waves were regular. This method had the disadvantage that the progress of the experiment could not be followed and measurements of wave-length had to be made on the paper. Subsequently a Cambridge recorder was used, the movements of the spot of light from the galvanometer being followed by hand. The drum of the curve tracer was driven through a gear and permitted the tracing of curves directly. The positions of maximum deflections were also simultaneously recorded. Some of the curves are given in Fig. 4. The record was used only to show the shape of the curve and to distinguish true from false maxima; readings of the positions of the maxima were made on the screw head.

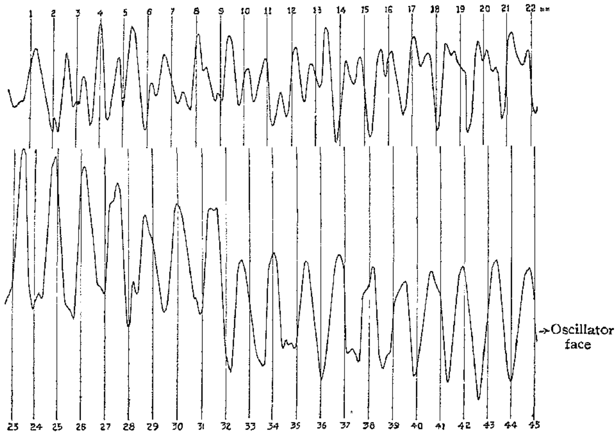

FIG. 2.

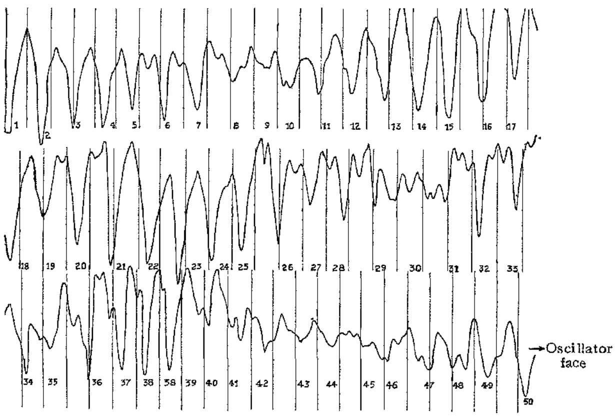

FIG. 3

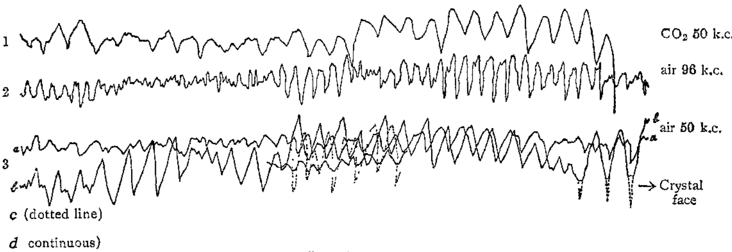

FIG. 4.

(*d*) *Quartz Oscillators.*—Two crystals were used for most of the experiments, their dimensions being 25.4 × 25 × 3.5 mm. and 54 × 22 × 3 mm. When these were placed in a holder of the usual type with the crystal resting on a brass plate, it was found that the smallest mechanical disturbance was liable to alter the amplitude of oscillation to such an extent that readings were unreliable. Much better results were obtained by silvering the crystal on one or both sides and thinly plating it with copper, the lead wire being directly soldered to the top. The plating changed the frequency of the crystal to a very considerable extent. A detailed report of this phenomena will be published in a subsequent communication (Part IV).

The smaller crystal could be made to oscillate at frequencies of 95, 130 and 750 kilocycles but the last two modes were difficult to excite and it was necessary to connect the crystal between the grid and plate of the valve for the purpose. With the grid filament circuit ordinarily used, only the 95 k.c. oscillation and its harmonics could be detected and there were no subsidiary frequencies in the neighbourhood of the main one. The larger crystal appeared to oscillate only at 50 k.c.

The main oscillation frequency of the smaller crystal was measured by comparing it with the sixth harmonic of an oscillator tuned to Rugby Wireless Station, the frequency of which was assumed to be 16.00 k.c. The pitch of the beat note was estimated with the help of tuning forks and the value found 95.0 k.c. was probably correct to 1 part in 1,000 and sufficiently accurate for the preliminary experiments. The frequency of the larger crystal was given by the makers as 50,000 cycles within 0.1 per cent. The plating changed this to 49,470 cycles (*cf.* Jatkar and Watson, *Electrotechnics,* 1932).

The temperature coefficient of frequency for each crystal was determined by adjusting an oscillating receiver to give a definite beat note (measured by a tuning fork) with the crystal oscillations. The crystal was then heated as rapidly as possible in an air-bath to a temperature ascertained by preliminary experiments in the neighbourhood of 100°, such that, the beat note frequency decreased to zero and rose again to nearly its original value, small differences being estimated by ear. The crystal was then cooled to ensure that there had been no change in the frequency of the oscillator. For a temperature increase of 80° the 95,000 cycle crystal decreased its frequency by 490 cycles and the 50 k.c. crystal, by 550 cycles. The temperature coefficients were thus 6.6×10^{-3} and $1.37 - 10^{-2}$ per cent. per degree.

2. Preliminary Experiments.

In the first experiment, the crystal was mounted on a block of wood and a glass plate 10 cm. × 8 cm. was used as a reflector. This was moved to within a distance of a few mm. in front of the crystal and deflections noted in the galvanometer for each 1/500 of an inch. These were plotted on a graph which showed that the amplitude (given within brackets) and spacing of peaks, were alternately high and low. The following table gives the readings:

Table I.

Frequency: 130,000 cycles.

Screw readings.

Bigger peak (1)	Subsidiary peak (2)	$\lambda/2$ (1)	$\lambda/2$ (2)
15·5 (28)		27·0	
	22·0 (13)		29·5
42·5 (29)		27·5	
	51·5 (18)		26·5
70·0 (26)		27·5	
	77·0 (8·5)		29·0
97·5 (29)		27·0	
	106·0 (7·5)		26·5
124·5 (35)			
	132·5 (7·5)		
	Average ..	27·25	27·8

The subsidiary peaks correspond to the presence of the first harmonic in the crystal vibrator. Peaks corresponding to the harmonic were small.

Further experiments were made in the small tube 30 cm. × 4 cm. It was found that although the setting of the resonance point was within 1/30 to 1/50 of a mm., the distance between the individual peaks varied more than 5 per cent. Further, the extent of resonance for subsidiary peaks was found to be unreliable as these changed in a very irregular manner. Assuming that the positions of the bigger peaks correspond to an integral number of half wave-lengths, the following average results for wave-lengths (λ) were obtained with the photographic recorder.

	f_1 95 Kc.	f_2 130 Kc.	Ratio λ_1/λ_2
$\lambda/2$ Air ..	1·88	1·37	1·37
,, CO_2	1·42	1·07	1·33

These results were obtained with the same crystal giving two frequencies. The difference in the ratio of the wave-lengths is obviously due to the dispersion of sound in CO_2 observed by Kneser (*Ann. der. Phys.*, 1931, **11**, 761).

The photographic drum was replaced by Cambridge curve tracer which has been used throughout this work and which served to bring out the complexity of the wave system for different positions of the reflector. Although these curves do not actually represent the wave form such as is obtained in the Kundt's dust figure method, the curves appear to be the resultant of more than one series of transmitted and reflected waves. It unfortunately happens that these curves can be caused by a number of factors probably all of which are at work, making all attempts at analysing the complexity of the wave form futile.

In the first place it is necessary to find the cause of the reaction current. The latter, no doubt, is the direct function of the pressure changes at the face of the crystal. In the case of our experiments there would be reflections from the sides of the tube. These were, on the first thought, regarded as producing a constant resultant reaction, the main pressure changes being due to the reflector perpendicular to the direction of transmission. The pressure will be minimum when the effective length is an integral number of half wave-lengths, and maximum when the effective distance between the reflector and the driving face of the crystal differs by quarter wave-length from that of the first adjustment. When the reflections arrive in phase with the oscillations there will be maximum pressure at the crystal and the anode current would decrease, and at the next setting of the reflector $1/4\lambda$ from the first setting the reflections arrive out of phase causing the pressure decrease and the resulting lower crystal potential will cause an increase of anode current. The latter position corresponds to the position of resonance and is characterised by its sharpness of setting, although in the case of vapours the maxima and minima are equally sharp owing to the increased amount of reaction of the denser vapour or gas. At the position of the reflector corresponding to resonance, the gas in which the stationary waves are formed will absorb the maximum energy from the circuit, and the anode current may increase just as in experiments with absorption wavemeter. On the other hand, the radiating resistance of the crystal ought to decrease and the crystal should oscillate with more amplitude resulting in a decrease in anode current. The actually observed change in anode current is thus the resultant of the two factors primarily affecting the grid potentials. These in turn are affected by the operating portion of the valve characteristic.

3. Velocity and Intensity.

Numerous causes have been given to explain the unequal spacing of the resonance positions in the supersonic interferometer. One of these reasons which might contribute to minor peaks is the presence of neighbouring frequencies in the quartz oscillator, which should, however, give an equally spaced peak. The records obtained in the present investigation show sets of satellites which are too irregular to be due to any neighbouring frequency. Pielemeier (*loc. cit.*) ascribes the satellites to the fact that supersonic waves in air have a velocity which depends upon their intensity and that this velocity approaches a limiting theoretical value at comparatively low intensities. The trend of the appearance of a major set of satellites and minor set of satellites is such that these satellites appear to merge into each other at greater path lengths, the merging occurring when the average speed for the first few return trips differs so little due to absorption, that a single reflector position serves as a common resonance position. For the shorter path lengths, the average speed for the first return trip is sufficiently high to require a separate resonance position. Pielemeier's evidence of the intensity effect is as follows: A slightly smaller major peak spacing was observed when the intensity at the source was decreased so as to produce peaks of about 1/10th of former magnitude. By covering the reflector with a blotter the spacing of the peaks was also decreased.

The evidence put forward by Pielemeier in favour of the intensity effect is not very sound. It is well known that the smaller the amplitude of the quartz source, the greater is the reaction of the sound field on resonance, showing major peaks depending upon the more favourable rectification by a change in the oscillating part of the valve circuit. It has been found throughout this present investigation that the magnitude of the peaks actually decreases by increasing the amplitude of oscillation by controlling the tuning of the anode condenser and by applying higher voltage to the valve. The curve 3 in

Fig. 4 shows the variations of the anode current for different positions of the reflector 5 cm. in diameter in an 8 cm. diameter tube using a quartz oscillator of 50 kilocycles in air. In the following table the positions for two typical sets of curves shown in dotted lines in curve 3, Fig. 4, are given. The reaction in 1 was 5 to 6 times that in 2. The galvanometer being shunted, the recorded peaks are not to scale.

TABLE II.

Curve *a*		Curve *c*	
Position mm.	$\lambda/2$	Position mm.	$\lambda/2$
92·75		92·75	
90·05	2·70	90·30	2·45
88·95	1·10	88·80	1·50
85·60	3·35	85·70	3·10
83·80	1·80	83·90	1·80
		82·20	1·70
78·70	5·10	78·10	4·10
75·90	2·80	75·95	2·15

The records in Fig. 4 were obtained when experiments were made in a tube 8 cm. in diameter using a 5 cm. reflector at 50 and 95 k.c. with carbon dioxide and air.

Curve 1 shows the record of the interferometer for carbon dioxide at 50 k.c.

Curve 2 shows the characteristic record for air at 95 k.c.

Curve 3 shows the record of the variations of the anode current for different positions of the reflector in air at 50 k.c. at room temperature with different anode couplings, *a, b, c* and *d*. Curves *a* and *d* have been obtained with maximum value of anode condenser and *b* and *c* (dotted line) with the lowest setting of the condenser. Increased reaction and simplification of the curves are noteworthy features when the crystal is oscillating on low power.

Although the peaks were shifted the average value of the wave-length is not appreciably changed. The observed spacing for half wave-length, therefore, seems to depend very much upon the valve characteristic, an effect which has been observed even with experiments in narrow tubes as will be described later, a mere change in grid leak producing profound changes in the spacing of the peaks.

There is no need to confuse the so-called intensity effect observed in these experiments where the power used was of the order of a micro watt, with the results of the abnormally high velocity of sound observed in the case of explosive waves.

4. The Effect of Harmonics.

Under ordinary conditions, the crystal oscillator gave weak harmonics as determined by a heterodyne receiver. With powerful excitation using 150 volts on the anode, it was found that the crystal oscillator responded to the first harmonic as well as the fundamental frequency to the same extent, at distances of reflector approximately corresponding to the integral number of half wave-lengths corresponding to both of these frequencies, with other irregularities.

5. Diffraction Effects.

It has been shown by Crandall (*Vibrating Systems and Sound*, p. 139) that high frequency waves starting from a circular radiating face of diameter 2R remain parallel up to a distance x on the axis of the transmitter, when the value x is given by the expression $m^2\lambda$, m being equal to R/λ where λ is the wave-length. Further, along the axis within the region $o < x < m^2$, there is a succession of maxima and minima of intensity analogous to the bright spots of optical diffraction phenomena due to the interference of waves from different positions of the radiator. And in the neighbourhood of x the waves begin to diverge into a beam of angle 2θ where $\sin\theta = \frac{0 \cdot 6\ \lambda}{R}$. It appears that this transition of a parallel to a diverging beam is accompanied by a change of phase. If now a reflector is moved in front of the radiator, the peaks and the nodes will be regularly spaced up to a distance of $x/2$, and for all positions of the reflector between $x/2$ and x the standing waves are made up of parallel direct waves and divergent reflected waves, making the resonance curve very complicated. The region of complex wave form on the above basis has been approximately calculated for the crystals used in these experiments. As the radiating side was a flat rectangle, the longest side of the rectangle has been assumed to be equal to 2R in the expression $x = m^2\lambda$. λ is the wave-length in the gas or vapour at the frequency F.

	F = 95,000	2R = 2·5 cm.	F = 50,000	2R = 2 cm.
	λ	x	λ	x
Air ..	·36 cm.	4·2 cm.	·7 cm.	1·3 cm.
Methyl ether ..	·26 ,,	5·4 ,,	·5 ,,	2·0 ,,
Ethyl ether ..	·20 ,,	7·2 ,,	·4 ,,	2·5 ,,

In Fig. 3 for methyl ether at 95,000 cycles which is reproduced from the photographic record, although measurements were made up to 67th peak which was very near to the crystal the curve is copied only up to 50th peak as the subsequent peaks were quite regular. It will be noticed that the complications start at peak No. 29 and end at 49th, a distance of 2.8 cm. which is roughly equal to $x/2$.

The actual phase shift in the transition of a parallel to a diverging beam is more difficult to find as the wave-lengths even in the region of regular peaks were not accurate enough.

According to Pielemeier (*loc. cit.*) the effects of diffraction calculated according to the expression given by Crandall, were negligible for one return trip from the source to the reflector and back, with the crystal he used and the short sound paths (actually 35 cm.) traversed. As he used the top of the crystal the variations observed ought to have been more pronounced. The apparent rise in the wave-length for regions close to the source observed by Pielemeier and more recently by Reid may be almost due to this cause, as the trouble comes in at lower frequencies and in the vicinity of the source.

In order to get reliable data, measurements should be confined to a distance of $x/2$ from the source or they should all be taken beyond x. Even in experiments done after removing other spurious effects this effect has probably crept in and will be discussed in a later communication.

The above considerations hold only as regards the axial radiation. As one goes further away from the axis in the region $o < x < m^2\lambda$ there will be maxima and minima of intensity, the angle of diffraction for the first minimum of intensity being .61 λ/R and .61 λ/R', where R and R′ are the two sides of the rectangle, the smaller side having a wider diffraction halo and *vice versa*. This calculation is based on the assumption that, the radiating face of the crystal is analogous to a rectangular aperture in a plane screen against which light waves are normally incident. The waves proceeding along these diffracted 'bright patches, will theoretically not be directly reflected back on the radiator by the position reflector' but may reach the radiator face, after being reflected by the sides of the tube in and out of phase with oscillation for various positions of the reflector. Grabau (*loc. cit.*) has, however, shown that these effects are not likely to be observed with the size of reflectors ordinarily used.

6. Effect of Screens.

Another possibility of extraneous source is the fact that the crystal can radiate sound waves both towards the reflector and upwards from the top electrode at right angles to the main radiation. This effect is small but still capable of producing the standing wave system for positions of reflector $(2n + 1)\ \lambda/2$ lengths from the rectangular crystal. That such is the case was proved by the fact that one could excite a wave system by using a round flat crystal with its radiating face at right angles to the reflector. Attempt was made to filter off this radiation by putting on an aperture of a size slightly smaller than the radiating face of the crystal, one cm. in front of it. The wave form was exceedingly complicated and the maxima considerably reduced.

The crystal was then covered up with cotton wool leaving only the face open. This helped to simplify the curve considerably, showing that there was a spurious source of radiation about the sides. This could not be studied further owing to the difficulty of making the crystal oscillate with cotton wool padded on. A wooden cover was made to fit the crystal loosely leaving the front open. The curve (Fig. 5*b*) shows the simplification of the original curve (Fig. 5*a*), which was obtained for air at 50,000 cycles in a tube 8 cm. $\times$ 35 cm. and using a reflector 5 cm. in diameter. The curve for carbon dioxide under the same circumstances as in curve *a* is given in *c*.

These results can be explained on the simple assumption that in the case of carbon dioxide owing to absorption, the effect of reflections from the various parts of the tube, is not enough to cause variations in the potentials of the oscillating crystal, and that in the case of air the spurious peaks observed are obviously due to stray reflections principally operating on the electrode face of the crystal. The wave form is too irregular to give any accurate results, as can be seen from the following table (Table III).

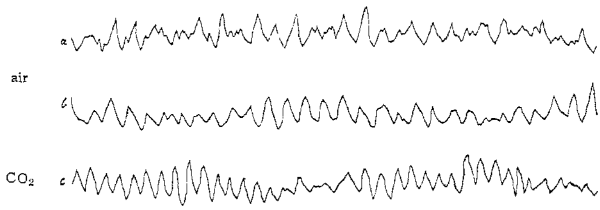

FIG. 5.

TABLE III.

Curve (*a*).

No.	Screw reading mm.	Calculated mm.	Deviation from $n\ \lambda/2$
	128·25	−3·50	
3	116·70	117·75	−1·05
4	112·10	114·25	−2·15
5	108·00	110·75	−2·75
7	100·55	103·75	−3·20
15	72·00	71·75	0·25
17	65·10	64·75	0·35
24	38·95	40·25	−1·30
25	35·20	36·75	−1·55

In Table III, the calculated values for the position of the reflector have been obtained by assuming the mean wave-length (3.50 mm. for air and 2.75 mm. for CO_2) and the deviations of the observed values from the calculated shown in column 3, clearly show the shifting of phase at different positions of the reflector in a very irregular manner and cause a serious difficulty in measuring the value of $n\ \lambda/2$.

Curve (*b*) Air.

No.	Screw reading mm.	Calculated mm.	Deviation from $n\ \lambda/2$
	133·40	− 3·50	
2	126·70	126·40	0·30
8	106·20	105·40	0·80
10	98·75	98·40	0·35
11	95·10	94·90	0·20
12	91·55	91·40	0·15
13	88·10	87·90	0·20
15	80·85	80·90	− 0·05
16	77·40	77·40	
17	72·65	73·90	− 1·25
19	66·55	66·90	− 0·35
20	63·10	63·40	− 0·30
24	48·95	49·40	− 0·45
27	38·40	38·90	− 0·50
28	34·75	35·40	− 0·65
29	30·55	31·90	− 1·35
30	27·20	28·40	− 1·20
31	23·55	24·90	− 1·35

Curve (*c*) CO_2

No.	Screw reading mm.	Calculated mm.	Deviation from $n\ \lambda/2$
	100·80	− 2·75	
1	98·15	98·05	0·10
2	95·55	95·30	0·25
3	92·65	92·55	0·10
4	89·95	89·80	0·15
6	84·25	84·30	− 0·05
7	82·50	81·55	0·95
8	78·95	78·80	0·15
9	76·20	76·05	0·15
12	68·45	67·80	0·65
15	57·20	59·55	− 2·35
17	54·65	54·05	0·60
18	51·65	51·30	0·35
19	49·00	48·65	0·35
20	45·90	45·90	
21	43·10	43·15	− 0·05
22	40·15	40·40	− 0·25
23	37·10	37·65	− 0·55
25	32·45	32·10	0·35
26	29·35	29·35	
27	26·45	26·60	− 0·15
29	21·90	21·10	0·80
30	18·10	18·35	− 0·25

7. Effect of Increasing the Area of the Radiating Face of the Crystal.

The radiating face of 50,000 cycles crystal was not quite square and might have introduced some irregularity in the waves. A microscope cover glass, 1 cm. in diameter, was cemented to this face and the wave-length and wave form determined in the usual way. It was found that the reaction was so big especially near the crystal, that, the latter stopped oscillating and no values of wave-lengths near the face of the crystal could be obtained. Fig. 6A (I & II) shows the result and Table IV shows the position of principal peaks.

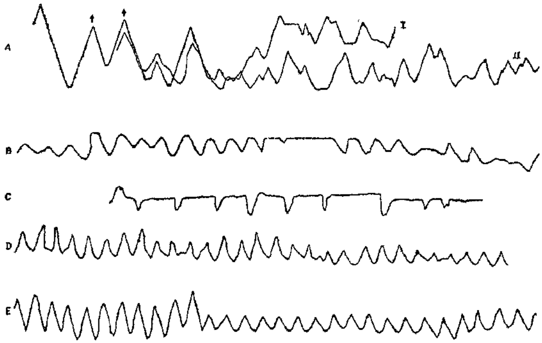

FIG 6.

TABLE IV.

F = 50,000.

Curve 6 A_I				*Curve* 6 A_{II}			
No.	Screw reading	Calculated value	Deviation from $n\ \lambda/2$	No.	Screw reading	Calculated value	Deviation from $n\ \lambda/2$
	105·00	− 7·50			105·20	− 7·87	
1	97·75	97·50	−0·25	1	98·20	97·33	−0·87
2	92·00	90·00	−2·00	2	87·20	89·46	+2·26
4	77·70	75·00	−2·70	3	81·50	81·59	−0·09
6	62·00	60·00	−2·00	4	71·50	73·72	+2·22
7	54·00	52·50	−1·50	5	68·60	65·85	−2·75
8	45·00	45·00	0	6	60·10	57·98	−2·12
				7	54·40	50·11	−4·29
	122·00	6·30		9	30·25	34·37	+4·12
2	111·60	109·40	−2·20	10	21·40	26·50	+5·10
3	105·25	103·10	−2·15	11	18·50	18·63	+0·13
4	98·65	96·80	−1·85	12	10·60	10·76	+0·16
5	92·00	90·50	−1·50				

A_I was obtained with the anode condenser at zero and A_{II} with the maximum setting of the condenser. The reaction in A_I was so large that the peaks marked with arrow head could not be followed on the curve-tracer although the galvanometer was shunted heavily. Most of the spacings correspond to at least double the velocity and those nearer the crystal were four times the usual wave-lengths. The longer wave-lengths were not due to the crystal vibrating at a sub-fundamental frequency due to loading by the cover glass. A search for this was made by a heterodyne wave-meter and non-oscillating detector. The only frequencies were 50,000 cycles and its harmonics. This phenomena cannot be due to the vibrations of the thin cover glass, as the wave form in that case, would be more complicated.

We might recall here the observation of Hitchcock (*Proc. Inst. of Radio Eng.*, 1927, **15**, 956) who obtained a velocity double that of ordinary in the electrode gap of a quartz oscillator, and cited it in proof of the idea that the velocity depended upon the intensity. It is rather difficult to understand how such a thing could exist in our experiments as the power used was the same throughout our other experiments, although more energy was transferred to the gas by the wider radiating surface. Reid (*loc. cit.*) used two crystals with different faces but having the same frequency and found that the face of the crystal affects the results when the reflector is close to the face but no large rise takes place. Further the cause of that rise cannot be due to intensity, as the energy radiated is small and the input to the crystal was less than 0.1 watt in his experiments.

8. Effect of Size of Reflector.

The remaining complications were thought to be due to the wide reflector which was 10–20 times the wave-length. Hence the next experiment was done using a piston rod, 1 cm. in diameter as a reflector in the 8 cm. diameter tube, the arrangement resembling that used by Reid (*loc. cit.*). The curve obtained is shown in Fig. 6 B which shows no spurious peaks, the positions of which are given in the following table. The average value of $\lambda/2$ is, however, about 1.3 times the ordinary value.

Curve 6 B (Fig. 6).

No.	Screw reading	Calculated value	Deviation from $n\ \lambda/2$
	101·00	4·62	
5	77·90	77·90	0
6	72·80	73·28	+0·48
7	68·50	68·66	+0·16
8	64·20	64·04	−0·16
	42·00	4·40	
1	36·90	37·60	+0·70
2	32·65	33·20	+0·55
5	21·35	20·00	−1·35
6	16·25	15·60	+0·65
9	1·90	2·40	+0·50

Special attention is drawn to the width of the resonance. The waves are still very irregular as can be seen from the deviation column.

9. Effect of Using Narrow Tubes.

The resonance peaks were considerably sharpened by putting a tube round the piston rod but fixed in the wider tube. The result is shown in Fig. 6 D which is free from the spurious and irregular peaks although the spacing is not quite satisfactory. The measurements are given in Table V.

Table V.

Curve 6 D.

No.	Screw reading	Calculated value	Deviation from $n\,\lambda/2$	No.	Screw reading	Calculated value	Deviation from $n\,\lambda/2$
	105·15	3·50		14	55·85	56·00	+0·15
1	101·50	101·50	0	15	52·35	52·50	+0·15
2	98·08	98·00	−0·08	16	48·90	49·00	+0·10
3	94·55	94·50	−0·05	17	45·40	45·50	+0·10
4	91·05	91·00	−0·05	18	41·95	42·00	+0·05
5	87·60	87·50	−0·10	19	38·50	38·50	0
6	84·00	84·00	0	20	35·00	35·00	0
7	80·40	80·50	+0·10	21	31·50	31·50	0
8	76·95	77·00	+0·05	22	27·90	28·00	+0·10
9	73·50	73·50	0	23	24·40	24·50	+0·10
10	69·90	70·00	+0·10	24	20·95	21·00	+0·05
11	66·48	66·50	+0·02	25	17·50	17·50	0
12	63·05	63·00	−0·05	26	14·00	14·00	0
13	59·55	59·50	−0·05	27	10·50	10·50	0

Although the variation in individual wave-lengths is 10 per cent. there is a maximum variation of .5 per cent. on the values of 20 $\lambda/2$.

An attempt was then made to improve on these results by detuning the anode condenser and putting in a grid leak. A very curious result was obtained. The anode current decreased sharply and the crystal was brought into oscillation at certain positions of the reflector more than a whole wave-length apart. This is shown in the curve Fig. 6 C and the position of principal peaks in Table VI.

Table VI.

Curve 6 C.

No.	Screw reading	Calculated value	Deviation from $n\,\lambda/2$
	34·70	6·72	
1	42·30	41·42	−0·88
2	49·20	48·14	−1·06
3	57·00	54·86	−2·14
4	54·60	61·58	−3·02
6	76·90	75·02	−1·88
7	85·00	81·74	−3·26
8	88·50	88·46	−0·04

Sliding the reflector further did not stop the oscillations as abruptly. The presence of a column of gas having a harmonic of the vibrating frequency of the crystal might have decreased its radiating resistance and the damping when just on the critical side of oscillation. The observed spacing however is more than a whole wave-length. It will be shown in a subsequent part, that, this result has led to the discovery of cavity resonance.

The microscope cover glass was removed and curves and wave-lengths similar to Fig. 6 D were obtained. The use of a plunger and tube 0.5 cm. in diameter gave similar results. The curve Fig. 6 E,

TABLE VII.

Curve 6 E. Pure air at 24·2° C. F = 50,000 cycles.

No.	Screw reading	Calculated	Deviation from $n\lambda/2$	No.	Screw reading	Calculated	Deviation from $n\lambda/2$
1	13·25	13·25	0	21	83·20	83·05	− 0·15
2	16·65	16·74	0·09	22	86·50	86·54	+ 0·04
3	20·22	20·23	0·01	23	89·95	90·03	0·08
4	23·68	23·72	0·04	24	93·48	93·52	0·04
5	27·05	27·21	0·16	25	96·98	97·01	0·03
6	30·80	30·70	− 0·10	26	100·40	100·50	0·10
7	34·22	34·19	− 0·03	27	104·05	103·99	− 0·06
8	37·35	37·68	+ 0·33	28	107·45	107·48	+ 0·03
9	41·28	41·17	− 0·11	29	110·98	110·97	− 0·01
10	44·65	44·66	+ 0·01	30	114·33	114·46	+ 0·13
11	44·75	48·15	0·40	31	117·90	117·95	0·05
12	51·22	51·64	0·42	32	121·40	121·44	0·04
13	55·00	55·13	0·13	33	124·90	124·93	0·03
14	58·60	58·62	0·02	34	128·30	128·42	0·12
15	62·00	62·11	0·11	35	131·85	131·91	0·06
16	65·60	65·60	0	36	135·28	135·40	0·12
17	69·10	69·09	−0·01	37	138·65	138·89	0·24
18	72·23	72·58	+ 0·35	38	142·40	142·38	− 0·02
19	75·78	76·07	0·29	39	145·92	145·87	− 0·05
20	79·65	79·56	− 0·09	40	149·45	149·36	− 0·09

was the best result obtainable by putting the crystal 5–6 cm. away from the narrow tube (1 cm.) and carefully adjusting its position until maximum reaction was obtained.

The average wave-length was accurate to one in 700, when the distance covered was equal to about 20 wave-lengths. Higher accuracy could be obtained by using longer tubes. Measurement of velocity of sound and corrections for the diameter of the tube will be discussed in Part V of this series.

10. Effect of Change in Valve Circuit.

One of the most astonishing results is the effect of change in the value of the grid leak in the oscillating valve circuit on the wave form even in the narrow tube. The results are given in Table VIII.

Table VIII.

A Grid leak 7 mm.		B Grid leak 3½ mm.	
Screw reading	$\lambda/2$	Screw reading	$\lambda/2$
		4·40	3·55
		7·95	3·45
		11·40	3·60
		15·00	3·45
17·30		18·45	3·30
21·70	4·40	21·75	3·55
24·15	2·45	25·30	3·60
28·70	4·55	28·90	3·60
31·20	2·50	32·50	3·40
35·55	4·35	35·90	3·50
37·90	2·45	39·40	3·40
42·65	4·75	42·80	
45·20	2·55		

The values for $\lambda/2$ in column A of the above table are alternately high and low; the averages of these pairs are in agreement with the values obtained in column B. Such values are obtained througout the present work. As the actual grid leak varied when passing vapours over the crystal, the external leak and the tuning were veried until tolerably good values for $\lambda/2$ were obtained.

Further examples of alternately high and low values of the wave-lengths are given in Table IX.

TABLE IX.

Position of the crystal at 8·00 mm.
Open end of 1 cm. tube at 9·00 mm.

A		B		A		B	
Screw readings	$\lambda/2$ mm.	Screw readings	$\lambda/2$ mm.	Screw readings	$\lambda/2$ mm.	Screw readings	$\lambda/2$ mm.
147·80				92·70	3·60	91·85	3·50
145·00						88·45	3·40
142·30	2·70			84·80		84·95	3·50
138·15	4·15	137·45		81·25	3·65	81·45	3·50
135·45	2·70	134·60	2·85	77·90	3·35	78·05	3·40
131·20	4·25	130·45	4·15	74·35	3·65	75·25	2·80
128·50	2·70	127·50	2·95	71·00	3·35	71·25	4·00
124·40	4·10	123·60	3·90	68·20	2·80	68·20	3·05
121·55	2·89	120·65	2·95	64·00	4·20	64·15	4·05
117·40	4·15	116·60	4·05	61·20	2·80	61·20	2·95
113·60	3·80	113·70	2·90	57·15	4·05	56·40	4·80
109·60	4·00	109·80	3·90	53·50	3·65	53·40	3·00
106·60	3·00	106·80	3·00			49·50	3·90
103·05	3·55	103·30	3·50			46·35	3·15
99·65	3·40	98·80	4·50			43·05	3·30
96·30	3·35	95·35	3·45			38·65	4·40
						35·00	3·65

The readings under A were obtained with condenser at zero and B with condenser at 110°.

It was interesting to note that when the values for wave-lengths are alternately high and low, the extent of peak is smaller and less sharp for the lower spacings. But the order seems to reverse at about 90 mm. from the face of the crystal.

One factor which may account for the alternately low and high values by increasing the anode coupling of the oscillator, is the displacement of the node from the boundary of the vibrating crystal which will behave like an yielding wall and cause absorption of sound energy. The bigger the amplitude the more the absorption and distortion of the standing wave system, as the face of the crystal does not, owing to its being not stationary, reflect the wave exactly 180° out of phase. The actual amplitude of the crystal however is of the order of a millionth of a millimetre and this will not account for the observed discrepancies.

Another cause of unequal spacing may be that owing to the dimensions of the radiating face, the condensation and rarefaction of air particles near the face may not be equally intense.

The possibility of two sources of waves, one having double the velocity and the other, a normal velocity slightly out of the phase was also considered. Attempt was made to filter out any such radiation by closing the narrow tube with an aperture 2 mm. wide and 1 mm. long. The reaction was considerably reduced and the maximum sensitiveness of the arrangement was employed. The average distance between two peaks of the same intensity was about 7.50 mm. corresponding to a velocity more than twice the ordinary. Subsequent experiments with tubes of different diameter showed that this apparent wavelength is due to volume resonance. This phenomena will be discussed in a subsequent paper (Part III of this series).

11. Experiments on Surface Waves.

An experiment to visualise the standing wave system in two dimensions such as the one obtained in our wide tube, was made by oscillating a rectangular plate in a rectangular trough of water. It was noticed that the standing waves were broken up by troughs and ridges like a cross-hatched pattern, there being no continuous wave front.

A more illuminating experiment was to produce ripples on the surface of mercury in a rectangular wooden trough, by means of an electrically maintained 25 cycles tuning fork, to one prong of which was fixed a plate of steel about 1″ wide, just dipping in mercury by means of a bent strip of iron, the other prong being weighted to obtain approximate balance of the vibrating system. With the fork maintained by minimum current in the coil, the standing wave pattern was regular and the number of half-waves could be counted for various positions of a glass plate reflector at which resonance occurred. The reaction of the latter made the fork go sufficiently strongly to produce a clatter against the core of the coil and served to indicate the position of maximum resonance. When the current was increased there were complications in the standing waves mainly due to the reflections from the sides near the radiator. Although the waves were quite regular a few wave-lengths from the face of the vibrator, at longer distances of the reflector there were complications near the oscillator face, which appeared to remain constant. The wave form near the reflector was of cross-hatched pattern. This phenomenon is no doubt due to reflection of the diffracted waves producing the interference pattern and is analogous to the results obtained with supersonic waves. Further, the difficulty of starting and maintaining the fork by the electrical contact had its counterpart in our 95 kilocycles crystal.

The main complications in the supersonic waves in air appear to arise out of the fact that the waves are not parallel. Rayleigh (*Theory of Sound*, 1894, 2, 161) showed that waves set up in a cylindrical tube will ultimately become plane, provided that the frequency is less than that of the natural transverse vibration of the tube, *i.e.*, if the wave-length exceeds 3.4 times the radius. Otherwise the sound pattern is immensely complicated by the transverse waves and the apparent internodal distance is liable to be in error. On this theory one will have to use tubes of less than one millimetre diameter to obtain parallel waves at the frequencies tried. But then the method is not sensitive owing to the reduced reaction.

The fact that it was possible to get nearly parallel waves even when the wave-length was 1/3rd the diameter of the tube shows that we are here dealing with the resonance of a pipe and the reactions of this resonance on the driving crystal, instead of the reaction of the standing waves between the reflector and the crystal. The increased accuracy obtained by the 'pipe' method is, no doubt, due to the fact that we are measuring the wave-lengths from nearly the end of the pipe, the position of which does not change when the wave-lengths are measured several half wave-lengths away from it.

The subsequent parts of this investigation will deal with Supersonic Satellites in vapours (Part II), Cavity Resonance at supersonic frequencies (Part III), Measurement of frequencies of Piezoelectric oscillators (Part IV), Supersonic velocity in air and steam (Part V), Supersonic velocity in vapours of acetone, ether and benzene (Part VI), Supersonic velocity in vapours of several organic compounds (Part VII), Calculation of Specific Heats from the supersonic velocity in gases and vapours (Part VIII).

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SUMMARY.

1. A simple arrangement has been described to record the 'wave form' in a supersonic interferometer either by a photographic method or directly on a Cambridge curve tracer.

2. Numerous curves showing the variation of anode current of the valve crystal oscillator with the position of reflector, in tubes of different diameters, in air, carbon dioxide and methyl ether have been recorded at 50 and 95 kilocycles. Some of the typical curves have been reproduced. Peaks corresponding to maximum electrical reaction were obtained at positions which were not integral number of half wave-lengths apart.

3. A detailed examination of the curves obtained has revealed the existence of complicated physical factors in the experimental procedure adopted by various workers in this field.

4. The consideration of diffraction and interference does not explain the irregular wave pattern observed even far away from the source. Even when the measurements are confined to the central sound beam, there is evidence to show changes in phase and intensity as the reflector is moved in front of the oscillating crystal.

5. The experimental results of previous workers in favour of the intensity effect on the velocity of sound have been shown to be due to the valve circuit. Minor changes in grid leaks and in the anode coupling condenser produced astonishing effect on the wave form.

6. The apparent wave-length was twice and even four times near the crystal when a cover glass was fixed to the radiating face of the crystal.

7. All the spurious peaks disappeared when a narrow tube was used, instead of using the interferometer system consisting of the quartz oscillator and a reflector in a big tube, and the wave-lengths could be determined to an accuracy of 1 in 700 even when 20 wave-lengths were measured, the increased accuracy being due to the resonating tube method of measuring the velocity of sound, the oscillating crystal behaving both as driver and resonator.

8. Experiments were conducted to visualise the standing wave system by producing low frequency ripples on the surface of water and mercury.

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