A PHOTOGRAPHIC METHOD OF FINDING THE INSTANTANEOUS VELOCITY OF SPARK WAVES.

BY ARTHUR L. FOLEY.

SYNOPSIS.

The velocity of explosive sound waves, determined by early investigators, is briefly discussed, particularly the several experiments of Mach and his associates on the velocity of spark waves.

A new and direct photographic method for finding spark wave velocity. A shadow of a sound wave produced by an electric spark near the center of a long light-tight rectangular box was cast on a dry plate at one end of the box by the light from a properly timed spark at the other end. A notched rim steel disk was rotated at a high and measured speed just in front of and parallel with the dry plate, the shadow of the disk covering but a narrow strip along one edge of the plate. Both the sound and light sparks cast notch shadows on the plate, the distance between the two shadows of the same notch giving the time interval between the sparks, and the sound wave picture the distance traversed by the wave in that interval. Plotting distance against time, the tangent to the curve at a given point gives the instantaneous velocity of the wave at that point. The formula used in calculating time intervals is derived and discussed.

Velocity almost normal except near the spark. Measurements were made on two hundred and eighty plates, for waves from 0.32 cm. to 50 cm. in radius, for both heavy and thin sparks, and for disk edge speeds of almost two hundred meters per second. A wave velocity double the normal at 0.32 cm. from the spark axis decreased very rapidly with increasing distance and at 2 cm. from the source was only slightly above normal. At points relatively near the spark where the intensity of the expanding wave was still great, the velocity of waves from heavy sparks was greater than that from thin sparks. Reference is made to corroborative results obtained by the writer when using two other photographic methods.

Sources of error in previous investigations eliminated by the photographic method. Previous investigators have found average and not instantaneous velocities. Since the velocity very close to the source is very high, average velocities run high. However, previous results have been entirely too high due to errors inherent in the experimental methods used. Attention is directed to several, the chief one being the use of tubes or "canals." The paper gives a photograph of a sound wave, a part of which has passed through a canal of the size used by Mach, the other part expanding freely into the space about the spark, showing the former wave thirty per cent faster than the latter—due to the lower average intensity of the expanding wave.

GENERAL AND HISTORICAL.

NEWTON'S equation for the velocity of sound, according to which all sounds travel at the same rate, was derived on the assumption of infinitely small displacements. Several writers have shown that the velocity of sound waves of finite amplitude is a function of the amplitude and therefore a function of the intensity. Numerous experimenters have verified the theory in the case of "sharp" sounds, such as are generated by electric sparks and quick acting explosives. Owing to its importance in war, sound ranging for instance, the velocity of sound produced by firing large guns has been studied extensively by military as well as by other investigators. Regnault[1] (in 1864), by electrically recording the reciprocal firing and the waves from two guns, found an average velocity of 331.37 m. per sec. for the first 1,280 m. from the gun, and a velocity of 329.9 for the next 1,165 meters. Jacques[2] (in 1879), using membrane receivers and a chronograph recorder, showed that the velocity of sound about a gun depends on the direction. For a cannon charged with one and one half pounds of powder the velocity immediately in the rear of the gun was below normal, and at 20 ft. the velocity was fifteen per cent. less than it was at 80 ft. behind the gun.

Wolff[3] sought to determine the nature of the disturbance resulting from an explosion and concluded that the type is essentially that of a sound wave, the velocity increasing with the violence of the explosion. Vieille[4] had previously found that he could obtain a wave velocity in air of 1,100 meters per second by sharpening the explosion of fulminate by tightly packing it. Both Earnshaw[5] and Riemann,[8] in a theoretical discussion of waves of finite amplitude, had shown that for such waves an increased velocity was to be expected.

In 1860 Earnshaw[7] derived an equation for the velocity of sound in air in which he did not assume, as did Newton, that the air is a continuous medium, nor was it necessary to apply the Laplace and Poisson correction. Earnshaw's equation makes the velocity of sound in air a function of both intensity and pitch, the effect of pitch being quite small. Earnshaw[1] concluded that "there is no other limit to the velocity with which a violent sound is transmissible through the atmosphere, than that which the possibility of supplying a sufficient degree of force in its genesis may impose. Hence it is probable that there is no sound which is propagated faster than a thunder clap, the genesis of which by the electric discharge being extremely violent and almost instantaneous, and accompanied by a large development of heat. If the

[1] V. Regnault, Mem. de l'Acad. Paris, 37, 1, 3, 1868; Comptes Rendus, 66, 209, 1868; Phil. Mag., S. 4, V. 35, 161, 1868.

[2] W. W. Jacques, Sill. Journ. (3), 17, 116, 1879.

[3] W. W. Wolff, Wied. Ann., 69, 329, 1899.

[4] P. Vieille, Comptes Rendus, 127, 41, 1898.

[5] S. Earnshaw, Proc. Roy. Soc., Jan., 1859, Vol. IX., p. 590.

[6] B. Riemann, Göttingen Abhandlungen, t. viii, 186, Abstract in Fortschritte der Physik, xv, p. 123.

[7] S. Earnshaw, Phil. Mag., June, 1860, Vol. XIX., p. 449, and Vol. XX., p. 39.

theory here advanced be true, the report of firearms should travel faster than the human voice; and the crash of thunder faster than the report of a cannon."

Earnshaw's prediction has been found to be true as far as the report of fire arms is concerned. As far as the writer knows, no trustworthy results have been obtained for the velocity of thunder. However, a large number of experimenters have worked on the problem of finding the velocity of waves from electric sparks. Although the energy involved in such sparks is not comparable to that in a lightning flash, nevertheless, the wave generation is "extremely violent and practically instantaneous," and an increased velocity of the spark wave near the source would be expected.

Most of the early work on the velocity of propagation of spark waves was done by using Antolik[1] figures, markings produced on a soot-covered or dusty plate by an electric discharge to or very near the plate. Antolik supposed the figures to be indicative of the nature of the electric discharge. They were later proven to be of acoustic origin.[2]

Mach and Gruss[3] studied the interference strips produced on sooty glass by two sparks or by a spark and its image by reflection, noting the displacement of the soot figures when one of the sparks was retarded by connecting Leyden jars in cascade and applying Feddersen's law to determine the time interval involved. They concluded (really assumed) that the velocity of their spark waves was about 400 meters per second. Mach and Sommer[4] continued the use of interference strips on sooty plates, but they resorted to experiment to determine the time interval between their sparks. One method was to set off the two sparks placed a known distance apart by firing a bullet between the two pairs of spark terminals, the speed of the bullet being determined by means of a ballistic pendulum. In another experiment it was found by firing a bullet horizontally through two vertical films supported on frames which were suspended some distance apart, and firing again when the two films were dropped simultaneously at the firing of the gun. The distance between the two holes in each screen gave the respective distances dropped through and by calculation the time required for the bullet to travel from the first to the second films, and finally the speed. Later they found it better to mount the two films at opposite ends of a rectangular box, to insure their simultaneous start. Still later they mounted the

[1] K. Antolik, Pogg. Ann., 151, 127, 154, 14, 1875.

[2] E. Mach u. J. Wosyka, Sitzungsber. der K. Gesellsch. der Wissensch. zu Wien, 72, 1875; W. Rosicky, l. c., 73, 1876.

[3] E. Mach und G. Gruss, Wien. Ber., 78, 14, 1878.

[4] E. Mach und J. Sommer, Wien. Ber., 75, 1877.

films at opposite ends of a shaft which was rotated at a high and optically determined speed. The results obtained by the ballistic method of determining the speed of the bullet range from 393 to 468 meters per second, for the velocity of a spark wave at distances of some 30 cm. from the source. The gravity method of obtaining the bullet speed gave even greater differences in the computed spark wave velocity. When two hammers were dropped simultaneously through unequal distances on fulminate of mercury the sound velocity ranged from 654 to 817 and 634 to 686, depending on whether the end of the tube in which the explosion occurred was closed or open. Although Mach and Sommer tried several other methods without obtaining results more consistent than those given above, nevertheless, they were able to announce that the velocity of an explosion sound wave depended upon its intensity, the method of its production, and the distance from the source. They classed spark waves as explosion waves.

A year later Mach[1] and his students published the results of an experiment in which they produced their interference figures on a soot covered revolving plate, the speed of which was determined stroboscopically. In one case the figures were obtained from the interference of the sound wave from a spark discharging directly to the rotating plate and the waves from a simultaneous (series) spark led to the plate through a tube of variable length. In another case, both sparks, connected in series, discharged directly to the rotating plate but at points some distance apart. One of the sparks produced a wave traveling in the same direction as the surface of the plate, the other a wave traveling in the opposite direction, the two waves interfering along a strip displaced toward the former spark. The former of the two methods appeared to yield the most consistent results. But as Mach's results do not agree at all with the results obtained by the writer, their discussion will be taken up in connection with the consideration of the writer's results,—after his method of determining spark wave velocities has been described.

Apparatus and Method.

The photographic part of the apparatus used in this investigation was very similar to that described by the writer in a paper on "A New Method of Photographing Sound Waves,"[2] to which the reader is referred for details not given in this paper.

The Leyden jars *L*, *L*, Fig. 1, charged by a Wagner static machine with two electrically driven revolving mica plates thirty inches in diam-

[1] E. Mach, O. Tumlirz und C. Kögler, Wien. Ber., 77, 1878.
[2] PHYS. REV., XXXV., No. 5, Nov., 1912, p. 373.

eter and yielding ten inch sparks, were discharged through the gaps *G*, *G*, the commutator *C*, and the two spark gaps *S* and *I*, connected in series. Partly by varying the relative lengths of the gaps *S* and *I*, but chiefly by varying the relative capacities *L* and *K*, the time of the illuminating spark *I* was made to occur a little later than the sound spark *S*, and to cast on the photographic dry plate *P*, a shadow of the sound wave produced by the spark at *S*.

A steel saw disk *D*, was mounted so as to be rotated at high speed parallel to the surface of the dry plate *P*, with the upper edge of the disk

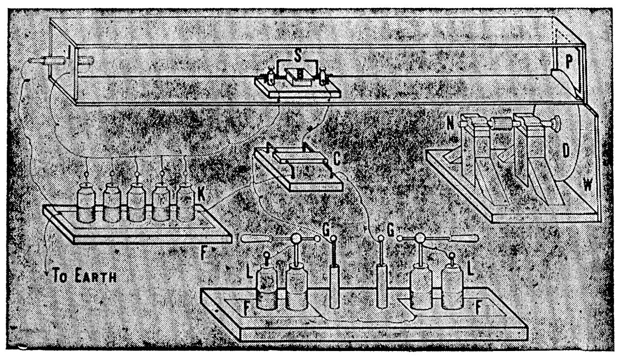

Fig. 1.

covering a narrow strip at the lower edge of the dry plate,—just enough to permit the shadow of the disk produced by the sparks at *S* and *I* to be photographed along with the sound wave shadow. The steel disk was made and mounted by a circular saw manufacturing company and was as well balanced as the manufacturer could make it. Several days were spent in testing the disk on knife edges and perfecting its balance. Notwithstanding the care taken in its making and mounting, it was thought unsafe to push the speed of rotation beyond eighty revolutions per second. As the disk was 239.39 cm. in circumference, this corresponded to a lineal speed of 191.51 meters per second, more than half the velocity of sound. At a slightly higher speed the disk began to warp and vibrate in a frightful manner. In coming up to speed the disk passed through two critical speeds at which there was some warping and vibration, but nothing compared to what a still higher speed called forth.

In partial explanation of the warping of the disk after so much work spent in balancing it, attention is called to the difference in air pressures on different parts of surface due to the fact that it did not rotate in the center of the light tight box in which it was mounted. The distance from the surface of the dry plate to the surface of the disk was but 1.5 cm., sometimes only 1 cm. Even when the distance was 1.5 cm. the disk was rotating within 1 cm. of the edge of the plate holder and about 1.3 cm. from the slide. The unbalanced air pressure on the slide was so great at the higher speeds that it could scarcely be moved in the holder.

The edge of the disk was ground (beveled) to a chisel edge with the plane side next the dry plate and 1.5 cm. from it (only 1 cm. distant during a part of the observations). Small V-shaped notches were made in the sharp edge of the disk by means of a small three cornered file held against the edge, at right angles to the plane of the disk, and tapped lightly with a hammer. The faces of the file had been ground smooth. The burr produced when the edge of the disk was dented (notched) was carefully removed by means of a smoothing file. The notches averaged about 2 cm. apart and were purposely made of various depths (.2 to 2 mm.) and at unequal distances in order to identify their shadows on the photographic plate.

The disk D was driven by means of a variable speed electric motor. The shaft of the disk was connected to a revolution counter and to a Van Sicklen-Elgin chronometric tachometer.

The first plan for controlling the sparks across the gaps G, G, was to place a glass plate transversely across the middle of each gap, the plates being fastened at one end to a wooden shaft by means of which they could be simultaneously rotated from between the gap terminals to permit the passage of a spark and rotated back to prevent a second spark. In practice, however, it was found much better to rotate the plates from between the terminals and to lengthen the two gaps G, G, until sparks ceased to pass. Sparks were then produced at will by a quick motion of the plates toward and away from the gaps. The lengths of the four gaps were varied from time to time along with the capacities L and K to obtain the desired time intervals between the sound and illuminating sparks. On the average, each of gaps G, G was made from 6 cm. to 8 cm. and S and I from 2 cm. to 3 cm. in length.

The Leyden jars used for the capacities L and K varied in capacity from 510 cm. to 536 cm. averaging 525 cm. The much smaller jar on the electric machine together with the capacity of the machine itself, appeared to be roughly equal to the capacity of one of the 525 cm. jars, and is so considered in the data recorded in this paper.

Care in arranging and adjusting the apparatus will not secure a uniform time interval between the sound and illuminating sparks. If one takes a sound wave picture and in an hour takes another, making no change whatever in the apparatus or its adjustment, the first time interval may be so short that the sound wave does not have time to get started, the second so long that the wave passes beyond the limits of the plate; or vice versa. However, most of this time variation can be overcome by frequently polishing the spark knobs (brass spheres about 2 cm. in diameter) of the spark gaps *G*, *G*, and by sparking the apparatus several times before making an exposure.

The procedure finally adopted was as follows: While an assistant *C* was bringing the disk up to speed, an assistant *R*, by rotating the glass plate previously referred to, produced sparks at regular time intervals, usually about three seconds. With eyes protected from the intense light of the illuminating spark by a pair of clouded glasses, and with a ground glass covering the end of the box instead of the plate *P* shown in Fig. 1, the writer viewed the shadow of the sound spark and adjusted the capacities and spark gap lengths until sound waves of the desired radius appeared on the ground glass. A long wooden bar, not shown in the figure, extending from the plate end of the box to a lever system at the illuminating gap enabled the observer to adjust the gap while viewing the waves. When once the capacities were adjusted to give waves, adjustment of the illuminating gap alone was sufficient to get them of any desired radius. This having been done, the ground glass was replaced by a dry plate and the exposure made by drawing the slide during the three second interval between the sparks. Tachometer readings of the speed of the disk were made immediately before, at the time of, and just after the exposure. Temperatures were taken both outside and inside the light tight box, the latter at a point near the sound spark gap. Finally, barometer and wet bulb hygrometer readings were taken, though not used in the calculations.

The sound and illuminating gaps, being placed longitudinally in the box, may be considered as point sources of light, as far as the plate *P* is concerned. When the sound spark occurred a shadow of the rotating disk *D* was cast on the dry plate, the V-shaped notches being clear cut, notwithstanding the high speed of the disk. Later the illuminating spark occurred and cast a shadow of the wave produced by the sound spark, together with a second shadow of the rotating disk. The distance between the two shadows of the same notch enables one to calculate the time interval between the sparks. From the radius of the wave shadow as measured on the plate, one readily calculates the actual wave radius. The quotient of the radius by the time might be supposed to give the average velocity. However, this statement involves two assumptions which the writer will call in question later.

To obtain pictures of waves greater than 15 cm. in radius, which otherwise would have been beyond the limits of the dry plate, a plane reflector was placed on each side of the sound spark gap, at such a distance from the gap that the wave, after any number of reflections, was always shadowed on the plate. In this manner waves were measured as large as 50 cm. in radius. There would have been no difficulty in extending the method to waves of much greater radius.

Figure 7 shows the vertical sound gap, the hot gases, the spark axis, the reflected wave and the notched edge of the rotating disk. Much of the detail, particularly the definition of the notches in the disk, has been lost in reduction and reproduction. In judging of the definition of the wave shown on this plate, one should remember that the sound spark is much nearer the dry plate than the illuminating spark and that nothing can be placed between the sound spark and the dry plate to prevent the light of the sound spark from fogging the plate as was done by the writer when he was using a horizontal sound gap. The light intensity of the illuminating spark must be many times that of the sound spark to obtain the definition shown on Fig. 1. The details of the illuminating gap are given in the writer's paper to which reference has already been made.

CALCULATIONS.

To determine from the distance measured on the plate the actual distance through which a disk notch turned during the time interval between the sparks, the writer assumes that the cord of a short arc of a disk thirty inches in diameter may be taken equal to the arc.

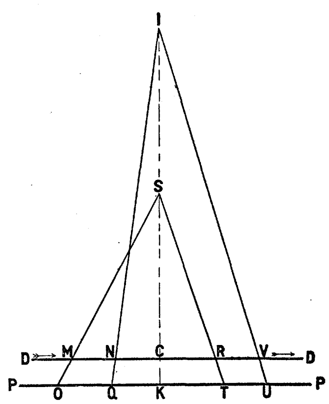

Fig. 2.

Figure 2 is a vertical projection in which I is the illuminating spark, S the sound spark, D the edge of the disk, P the edge of the dry plate. Suppose the disk moving rapidly in the direction of the arrows. When the sound spark occurs at S the shadows of notches M and R are cast at O and T respectively. By the time the illuminating spark occurs at I, the notches M and R have moved to N and V, and their shadows are cast at Q and U, respectively. Let C and K be points on the disk and dry plate, respectively, and on a straight line through S and I.

Let

$$MN = d,$$
$$RV = d',$$
$$OQ = X,$$
$$TU = X',$$
$$QK = D,$$
$$KU = D',$$
$$\frac{SC}{SK} = a,$$
$$\frac{IC}{IK} = b.$$

Then

$$\begin{aligned} d &= a\cdot OK - b\cdot D \\ &= a(OK - D) + (a - b)D \\ &= ax + (a - b)D, \\ d' &= bD' - a\cdot KT \\ &= a(D' - KT) - (a - b)D' \\ &= ax' - (a - b)D'. \end{aligned}$$

But

$$d = d' = \tfrac{1}{2}(d + d'),$$

(1) $$d = \tfrac{1}{2}[a(x + x') + (a - b)(D - D')].$$

The following are the dimensions used during the greater part of this investigation:

$$SC = 148 \text{ cm.}, \qquad SK = 149.5 \text{ cm.}, \qquad IC = 277.3 \text{ cm.},$$
$$\text{and} \qquad IK = 278.8 \text{ cm.}$$

Using these dimensions to obtain the values of a and b and supplying in (1)

(2) $$d = .495(x + x') - .0023(D - D').$$

The "constants" appearing in (2) were varied occasionally by changing the distance between the disk and dry plate, a ranging in value from .495 to .493 and b from .0023 to .004.

Let t = the time interval between the sound and illuminating sparks, $2\pi r = 239.39$ cm. = circumference of disk, n = number of revolutions of the disk per second:

(3) $$t = \frac{d}{2\pi rn} = \frac{d}{239.39 \times n} \text{ seconds.}$$

The value of d given by equation (2) was checked as follows: With the disk at rest, a dry plate in position and the illuminating gap short circuited, a spark was sent through the sound gap. The disk was then rotated a measured distance, the sound gap short-circuited and a spark passed through the illuminating gap. The measured value of d and the value calculated from the plate by equation (2) agreed to within 0.1 per cent. A higher degree of accuracy in measuring d, and therefore in measuring the time interval t, is not necessary, because the radius of a wave near the source can not be measured to any higher degree of accuracy. The wave shadow fades out more or less gradually on each side of the point of maximum density. Consequently one can not locate exactly the wave front. Then, too, the changing form of the wave and its variation in intensity affect somewhat the distribution of light in the wave shadow.

Results.

Altogether the writer made measurements and computed the velocities of the waves on two hundred and eighty plates. Some of the data and results are given in Table I., the only point considered in their selection being to show waves of widely different radii.

Table I.

Plate Number.	x', Cm.	D', Cm.	D, Cm.	x, Cm.	d by Equation 1, Cm.	Wave Radius.		Disk Turns per Sec.	Time Sec.$\times 10^4$.	Wave Velocity.	
						Measured on Plate, Cm.	Actual (Calculated), Cm.			"Average" Radius Time, M.	Instantaneous from Curve, M.
143	0.021	2.1	7.2	0.057	0.03744	0.75	0.349	58.9	0.2687	1,295	678
111a	0.063	3.0	1.7	0.098	0.08415	1.11	0.615	34.82	0.8851	695	546
123a	0.216	1.16	6.24	0.274	0.2213	2.27	1.247	41.83	2.216	562	423
124a	0.85	4.35	3.9	0.91	0.7686	6.4	3.52	41.5	7.759	454	383
123K	1.87	3.6	3.9	1.93	1.8718	13.15	7.48	41.07	18.82	398	358
1253	5.4	0.0	0.0	4.0	9.312		33.86	41.5	93.97	360	357

Figure 3 is a plot of time and wave radius. Inasmuch as it is not practicable to show two hundred and eighty points on so small a scale, most of the points represent averages of several time and space measurements, the circles for strong sparks, the dots for weak sparks. For strong sparks each of the capacities L, L, Fig. 1, consisted of seven jars (525 cm. each) and K of eighteen jars; for weak sparks, two and six jars respectively.

The tangent to a curve drawn through these points gives the instantaneous velocity of sound at a distance from the source corresponding to the point at which the tangent is drawn. In Fig. 3 the writer has drawn a straight line at a slant corresponding to an average sound velocity of 354 meters per second. Inasmuch as the experimental observations were made at a temperature of 24° C., at which the normal velocity of sound is 346.8 m. per sec., and the straight line appears to

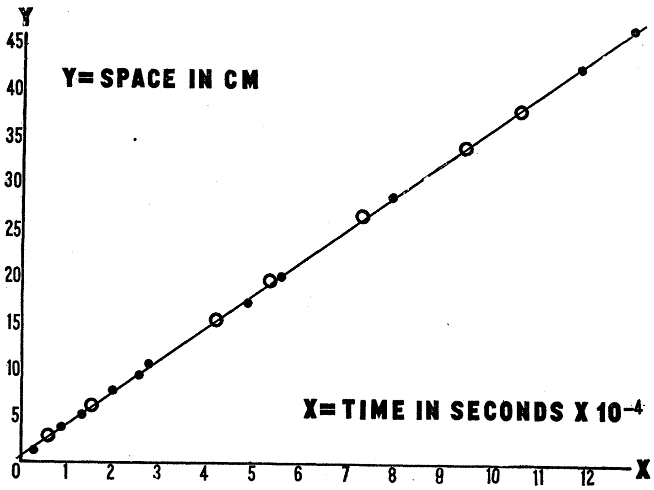

Fig. 3.

fit the data fairly well, it might be inferred that the velocity of a spark wave is constant and slightly greater than normal. But when the plot is made on a much larger scale, and for points nearer the sound source, Fig. 4, one sees that the velocity of a spark wave is not constant in this

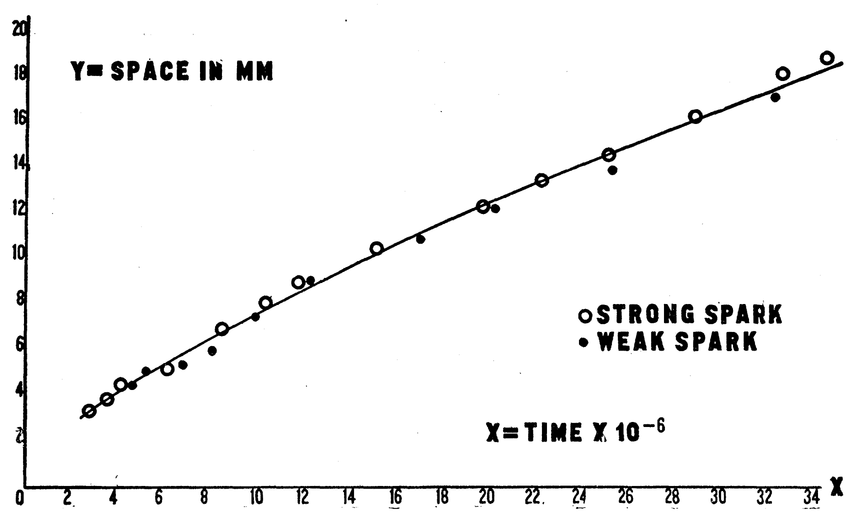

Fig. 4.

region. Note that observations have been made at points as close as 3 mm. from the spark axis. Note, too, that the curve, if continued regularly, would not pass through the origin. The writer is studying the spark itself and will have something to say later about what happens in this region. It is evident, however, that the velocity of sound at points near the source can not be determined accurately by any method which involves the ratio of total space to total time. This ratio, for the nearest point on the curve, gives an average velocity of 1295 m. per sec., while the tangent to the curve at that point gives an instantaneous velocity of 678.6 m. per sec. The last two columns of Table I. give average and instantaneous values for other and more distant points. These values approach one another as the distance from the source increases but at points near the source they are widely different.

An ordinate of Curve I of Figure 5 gives the *instantaneous velocity* of a

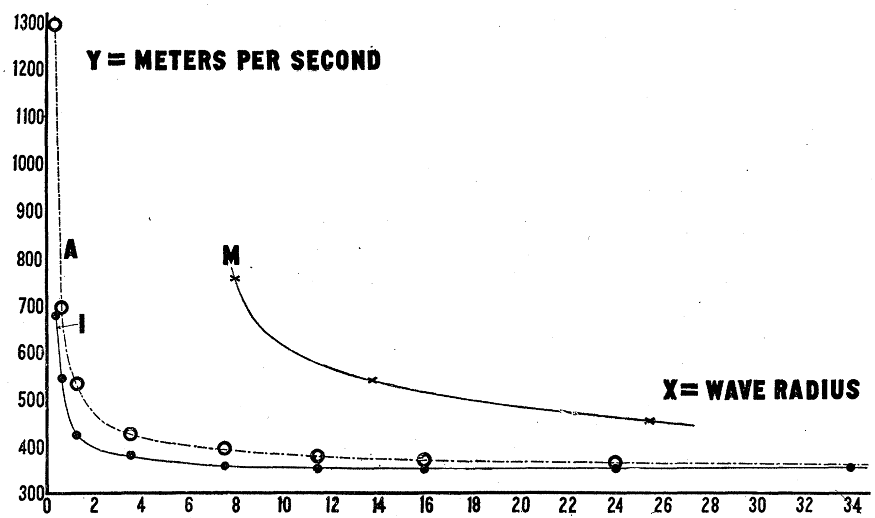

Fig. 5.

spark wave as it passes a point whose distance from the source is the abscissa. An ordinate of Curve *A* gives the *average velocity* for the corresponding distance from the source, both *I* and *A* being plotted from the writer's measurements. Curve *M* is an *average velocity* curve plotted from Mach's measurements.

Comparing curves *M* and *A*, one observes that the spark wave velocities obtained by Mach are much higher than those obtained by the writer, and that they decrease much less rapidly with increasing distance from the source. The lack of agreement is doubtless due in large measure to a difference in the intensity of the sound waves used. Fig. 4 shows a slight difference between the velocities of waves produced by strong and weak sparks. But the writer's strongest sparks were much less intense than those used by Mach. However, the question of the intensity of the sparks would have been of much less moment had Mach experimented with spark waves in free air. The intensity of such waves near the source decreases so rapidly with increasing distance that a high initial velocity soon becomes almost normal. But if the spark wave is generated at or near the end of a tube the initial energy of the portion of the wave entering the tube remains more nearly constant, giving an increased velocity through the tube, as the writer has previously shown.[1] As a

[1] PHYS. REV., XIV., No. 2, Aug., 1919, p. 143.

matter of fact, in most of the work done by Mach and others on the velocity of spark waves near the source, the observers have passed the waves through "canals." Figure 8 shows photographically what

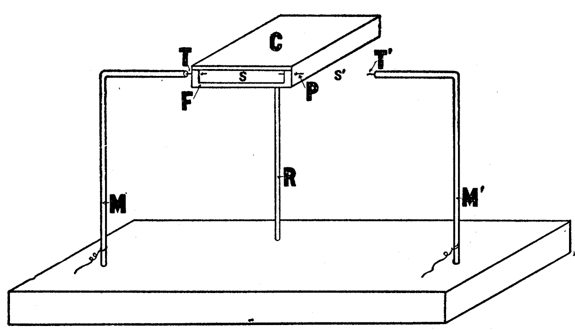

FIG. 6

Fig. 6.

happened when the writer produced a wave by a spark in the end of a rectangular canal of the size used by Mach. Fig. 6 shows the arrangement of the apparatus at the sound spark.

A rectangular tube was made by planing a groove 3 mm. deep and 1.8 cm. wide in a block of insulating fiber *F*, 5 mm. thick, 2.5 cm. wide and 6 cm. long, and covering with a piece of fiber *C*, 1 mm. thick. At *T* and *P*, 1 mm. from the end of the tube, holes were bored through the walls. One of the platinum terminals of the sound spark gap extended through one side wall of the tube. A short piece of platinum wire extended through the other wall. Thus the sound gap *TT′* was broken into two halves, *S* and *S′*. A spark wave produced at *S* was forced to travel 6 cm. through the rectangular tube before emerging into free air, while the wave produced simultaneously at *S′* was free to expand from the start.

Figure 8 shows that the wave through the tube is considerably in advance of the one in free air. Calculation shows that the wave velocity in the tube for "strong" sparks was some twenty-two per cent. greater than the velocity in free air. For weak sparks the velocity difference was somewhat less.

Much of Mach's work was done with a tube closed at the spark end. When the writer closed the end of the tube leaving everything else as shown in Fig. 6, he found a wave velocity in the tube more than thirty-five per cent. greater than the velocity in free air. For as heavy sparks as those used by Mach, doubtless the velocity differences would have been still greater. In short, we have here at least a partial explanation of the very high spark wave velocities obtained by several previous experimenters and of the lack of agreement between their results and those obtained in this investigation. It is clear that sound waves should not be confined in small tubes or "canals" in any investigation involving their velocity in free air.

The method described in this paper is the writer's third one, the first two having been published previously.[1] While the third method gave more uniform results than either of the others, their averages are in good agreement and confirm the conclusions stated below.

Summary and Conclusions.

1. The instantaneous velocity of a spark wave has been determined by a photographic method which is free from the various sources of error of previous methods.

2. Heretofore no velocity measurements have been attempted at points nearer than 8 cm. from the spark. This investigation carries the measurements to within 0.32 cm. of the source.

3. The instantaneous velocity of spark waves was found to depend on wave intensity and therefore to depend on both spark intensity and distance from the source.

4. A spark wave velocity almost double the normal velocity of sound at 0.32 cm. from the source decreased to almost normal at a distance of only 2 cm. from the source.

5. The very high velocity obtained by Mach at 8 cm. from the source is explained as due in part to the use of very heavy sparks, but chiefly as error inherent in the methods used.

6. The writer shows photographically that the velocity of spark waves through canals such as used by Mach is far greater than the velocity of the same wave in free air, and that the velocity in a canal increases with the intensity of the spark.

[1] A. L. Foley, Proc. Indiana Acad. Science, 1919, p. 221.

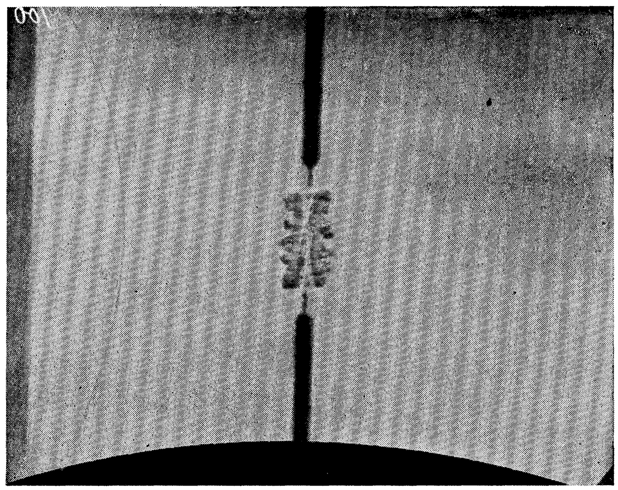

Fig. 7.

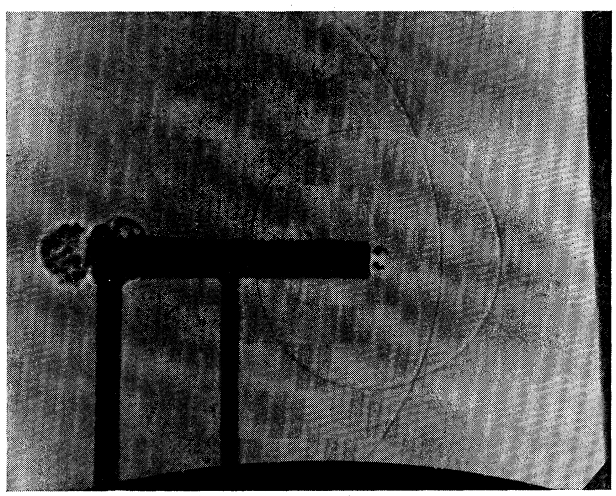

Fig. 8.

ARTHUR L. FOLEY.

7. Due to the motion of the air set up by a rotating disk measurements of sound wave velocity near the surface of the disk are wholly unreliable.

8. Owing to the practically instantaneous generation of a spark wave and its first appearance at some distance from the spark axis, the quotient of wave radius by time (for points near the source) gives an "average velocity" much greater than the instantaneous velocity at the nearest point at which the wave can be differentiated from other spark phenomena.

The writer wishes to acknowledge the aid given him in this research by a grant from the American Association for the Advancement of Science.

Waterman Institute for Research,
Indiana University,
May, 1920.

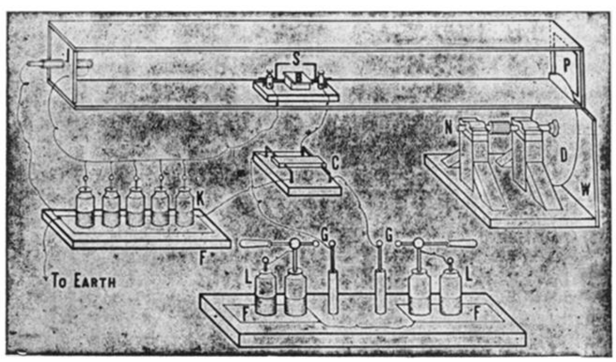

Fig. 1.

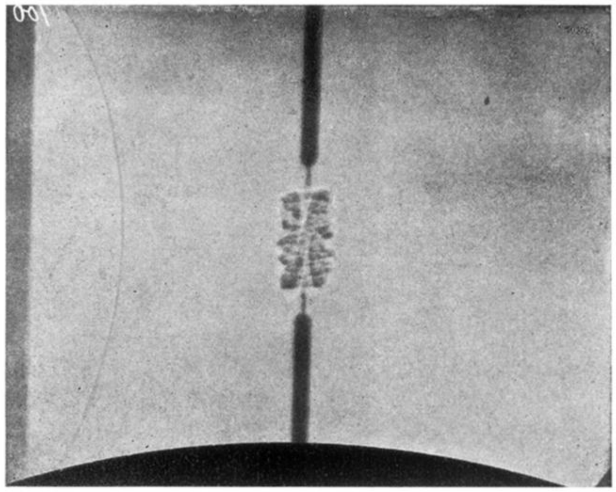

Fig. 7.

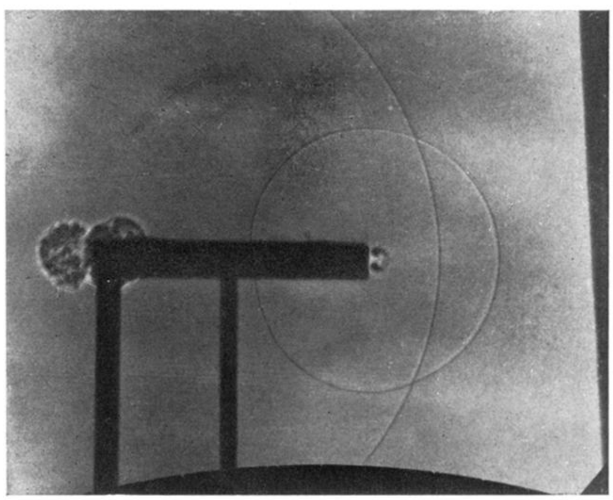

Fig. 8.