ON THE WAVE-FORM OF A SOUND PRODUCED BY A SPARK

By J. Okubo and E. Matuyama
Sendai, Japan

(Received August 12, 1929)

Abstract

By using Michelson's interferometer, the wave-form of a sound produced by a condensed spark has been studied. It has been found that the wave consists of a high frequency oscillation of air of the order 10^{-4} sec., having two discontinuities, one being due to a condensation at the head and the other to a rarefaction at the tail. The variation of the wave-form has also been observed, as it propagates onwards.

Introduction

Following the well-known experiments by E. Mach and his co-workers,[1] many well-designed and interesting devices for measuring the velocity of the sound waves produced by a condensed spark at points both near and distant from the source have been brought out by M. Toepler,[2] A. L. Foley,[3] J. E. Smith [4] and others. And the law governing the relation between the propagational velocity of the disturbance of air in a free atmosphere and the distances from the source of the points of observation have been fairly reliably established.

Notwithstanding its importance as a fundamental problem in a physical as well as a physiological sense, it is to be regretted that as regards our knowledge of the precise nature of the wave-form of air disturbances especially in such a case as that of a powerful explosion of an explosive material or of a condensed electric discharge, we are quite in the dark.

In all previous works on the visualization or photographic record of the sound wave obtained by the so-called "Schrieren Method," it is pointed out that the wave-shadow always stands out with surprising distinctness. This means that the density of the air is abruptly increased by the arrival of the sound wave and then suddenly decreases. But it must be here taken into consideration that this wave-shadow has been produced by a beam of light which has undergone complex refraction from the spherical or cylindrical layers of condensed and rarefied air and obviously the true variations of the density in the air cannot be determined from these records.

One type of apparatus for the registration of the wave-form of the sound is the so-called "Phonodeik" which is a device for the utilization of a mem-

[1] E. Mach and Gruss, Wiener. Ber. **78**, 14 (1878); **98**, 1257 (1889).
E. Mach and Salcher, Wied. Ann. **32**, 277 (1888).
[2] M. Toepler, Ann. d. Physik **14**, 838 (1904).
[3] A. L. Foley, Phys. Rev. **16**, 449 (1920).
[4] J. E. Smith, Phys. Rev. **25**, 870 (1925).

brane or a thin plate, as is done in the apparatus constructed by K. Marble,[5] D. C. Miller,[6] C. V. Raman and A. Dey,[7] S. H. Anderson[8] and others.[9] These methods are very convenient and fairly sensitive. But though they may be suitable for the sound of a comparatively low frequency, they may not be adapted for one of a higher frequency.

S. Garten[10] has also devised a faithful sound register consisting of a soap film which is very thin and of small area, and by recording photographically the motion of iron file-dust placed on the film, he has obtained various records of the wave-form of the air disturbances produced by a tuning fork, an organ pipe, vowel utterance, and the detonation of a condensed electric discharge. But it is evident from his records as well as from his conclusions that in using this register the resonances of a small air cavity attached behind the film cannot be completely obviated when the frequency of the sound is high, and it is not easy to determine precisely the true wave-form of the detonation.

Recently other types of electrically registering devices have been brought out by E. C. Wente,[11] H. Riegger,[12] J. Obata,[13] and W. Einthoven and S. Hoogerwerf.[14] These methods are of great sensitiveness but they also depend upon the utilization of the vibration of a thin plate or of a fine string, and the wave-form registered by this means will have the same defects as that of the former type of apparatus. As F. Auerbach[15] and S. Garten[10] have pointed out, it seems that the detonation is a very rapid motion of the air particles and so for the registering of such a high frequency disturbance, the common type of phonodeik which has been mainly used in the study of the sound waves of comparatively low frequencies will be inadequate. To obtain the precise form of a detonation wave accurately it will be absolutely necessary to devise a registering system having an inertia no greater than that of an air particle itself.

Already A. Raps[16] has used a Jamin type of interferometer as a sound recorder and has recorded the density variation due to the sound wave produced in a gas which the light traverses. This method is theoretically quite free from any objection, and it might be expected that with it the precise form of the air disturbance would be accurately obtained, but as he remarked, it is to be regretted that the sensitiveness was not sufficiently great to enable the fine form of the wave to be recorded.

[5] K. Marble, Zeits. f. Psychol. **49,** 206 (1908).
[6] D. C. Miller, The science of musical sounds, 1916.
[7] C. V. Raman and A. Dey, Phil. Mag. **39,** 145 (1920).
[8] S. H. Anderson, J. Optical Soc. Am. **11,** 31, (1925).
[9] The full literature is summarised in Handbuch der Physik VIII, p. 596, p. 606, (1927).
[10] S. Garten, Ann. d. Physik **48,** 273 (1915).
[11] E. C. Wente, Phys. Rev. **10,** 391 (1917); **19,** 498 (1922).
[12] H. Riegger, Siemen. Konz. III,2, 67 (1924).
[13] J. Obata, Jour. Franklin Inst. **203,** 647 (1927).
[14] W. Einthoven and S. Hoogerwerf, Pfluger. Arch. f. Den. Gesell. Physiol.
[15] F. Auerbach, Winkelmanns Handbuch d. Phys. Akustik, p. 276, 1909.
[16] A. Raps, Wied. Ann. **50,** 193 (1893).

To obtain an accurate record of the precise nature of the density variation of the air due to a rapid disturbance caused by a condensed electric discharge, we have adopted an interferometer method, and have used Michelson's type of interferometer. By this method some interesting records were obtained, and in what follows we shall describe the arrangements of the apparatus and the main results obtained.

The Experimental Arrangement

The main arrangement of the apparatus used is shown diagrammatically in Fig. 1. In order to introduce the sound wave, a short tube was firmly fixed on the interferometer, across the pencil of the light, between the two

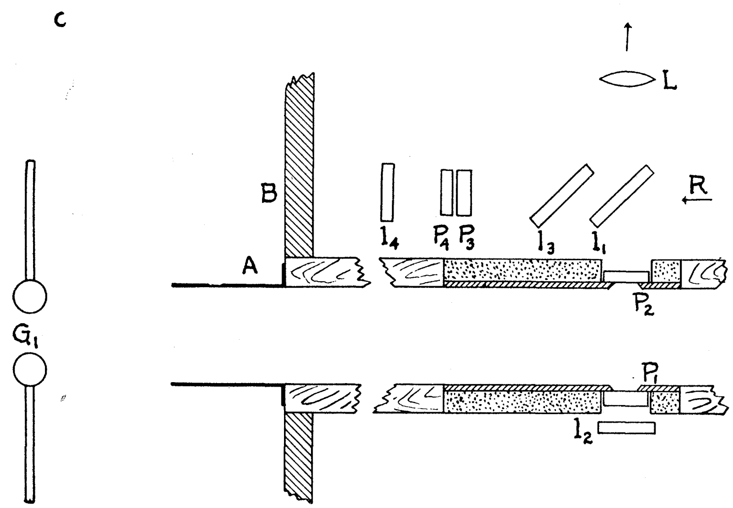

Fig. 1. Diagram of apparatus in plan.

mirrors l_1 and l_2. The tube in cross section is a rectangle having an area 5.1×5.5 cm^2, and is 14.0 cm in length; it was made of a brass plate 2 mm in thickness covered with a sheet of felt 1.2 cm thick, to protect the surrounding space from the disturbance. The tube has two windows on both sides towards two mirrors l_1 and l_2 and on each of these windows a small plane and parallel plate of glass P_1 and P_2 1 cm in thickness and of an area 2.0×2.0 cm^2 is cemented firmly with Canada balsam. The distance between the internal surfaces of these glass plates was 5.9 cm. For the purpose of compensation another pair of plane and parallel plates of glass P_3,P_4 was placed between two other mirrors l_3,l_4 of the interferometer.

As a source of the detonation wave, a spark gap G_1 was used and in what follows this gap will be referred to as the sound gap. To restrict the condition of the sparking, the spark length was always maintained at 2.6 cm, the spark always taking place in a free atmosphere. At a distance of 30 cm from the sound gap, a wide cork plate B 55×55 cm^2 in area was placed, which has a rectangular hole in the center. This hole has an area of 5.1×5.5 cm^2 and attached to it are two short tubes having the same cross section. One, A, which faces towards the sound gap G_1 is made of thick paper and is 7 cm in length, the other facing towards the interferometer is of dry wood and is connected with the other tube by a rubber band. After several trials, it was confirmed that at this distance between the cork plate and the sound gap, and with the precautions taken at the hole, any complications arising from reflections or diffractions of waves at the mouth of the tube could be completely obviated as the wave-length is short compared with the sectional dimension of the tube. The disturbance entering the observing tube is to be considered a plane wave. The wave diffracted from the edge of the cork plate arrives also at the observing space somewhat later and after the main wave has already passed through that space. We can distinguish them on the photograph.

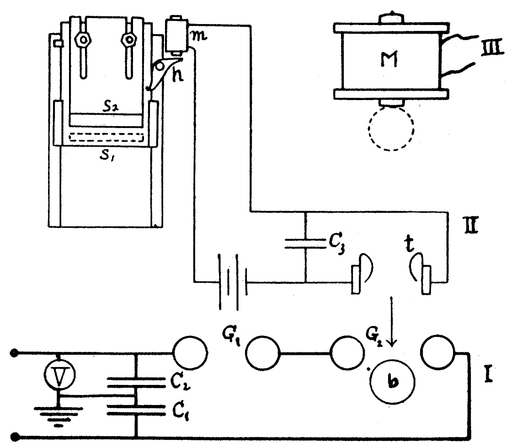

Fig. 2. Circuit diagram of shutter and spark system.

The time-interval in which the detonation wave is passing through the observing space is very short in duration, and therefore to obtain a record of the displacement of the interference fringes in this short interval it is necessary to devise a means by which the whole arrangement operates effectively and automatically. For this purpose, the following arrangement as shown in Fig. 2, was adopted and worked quite satisfactorily. Circuit 1 contains the sound gap G_1, another gap G_2, which will be referred to as the starting gap, and a Toepler influence machine (plate number 35) in series, with two Leyden jars C_1, C_2 having a capacity of 0.0029 m.f.d. and a kilo-voltmeter V in parallel. The inductance of this circuit was not measured, but from the construction of the circuit, it is estimated to be very small. Circuit II contains a small coil with an iron core m, a gap t made of elastic brass strips, which will be called the contact gap, and secondary batteries in series, with a large condenser C_3 in parallel. Circuit III contains a coil with a soft iron core M, batteries and a key in series. They were carefully adjusted so that the three centers of the coil M, the contact gap t, and the starting gap G_2 come on one and the same vertical line and the distance be-between them can be altered at will.

The photographic system consists of a rectangular camera box and a shutter system specially designed. A rotating drum round which the photographic film is wound is placed in the box; the diameter of the drum is 15.3 cm and the rotational velocity can be regulated in the range of from 2500 to 3800 revolutions per minute by varying the current intensity passing through a d.c. motor. The shutter system is attached on one side of the box and consists of two parts; the fixed slit s_1 of an area 3.5×6.0 mm,[2] and the other slit s_2. The latter can be moved freely over the former, and its breadth is made adjustable in order to control the duration of the exposure. On one side of this slit near the coil m in circuit II a small hook h of soft iron is provided which rotates round an axis. By passing an electric current through circuit II, the coil m attracts one end of the hook h and the movable slit s_2 falls easily over the fixed one. Thus the light from the interferometer falls on the photographic film at the proper moment and for the time-interval required.

The light from an arc lamp falls on the mirror l_1 of the interferometer in the direction as shown by the arrow R in Fig. 1, and after passing through the interferometer and the condensing lens L forms a 3.5 times magnified image of the interference fringes on the film. To protect the light intensity from the loss due to the several reflections and to shut out the disturbing light flux, we have used, as A. Raps did, a large condenser 22 cm in diameter, a diverging lens, with a slit between the diverging lens and the first mirror of the interferometer. By means of a cylindrical lens of short focal length inserted in front of the film, a well illuminated sharply defined image of the fringes was obtained on it. As the heating effect of light carries the fringes continuously in one direction, frequent adjustment was required to bring the white fringe back to the center before we could get any photograph.

Experimental Results and Discussion

At first, after closing circuit III containing coil M, a small iron ball b was put in contact with the core of the coil, the distance between coil M and the contact gap t, and that between the gap t and the starting gap G_2 being properly adjusted. Then, two Leyden jars C_1 and C_2 in circuit I were fed by the influence machine until the voltmeter showed the constant voltage, 34 K.V.

On opening circuit III of the coil M with the key, the ball b falls down between the contact strips t and closes circuit II, coil m attracts one end of the hook h and the movable slit slides over the fixed one. After a lapse of time as short as that taken by the ball to fall from the gap t to the gap G_2 intense sparks are emitted at the starting gap, and at the sound gap simultaneously, and the disturbance of the air propagates into the observing tube. By properly adjusting the distance between coil M and the contact gap t and that between the contact gap t and the starting gap G_2, it is possible to open the slit at the right moment, and to allow the light to fall from the interferometer and the lens on the the film for the required time-interval during which the wave is passing through the observing portion of the tube.

Thus by opening circuit III only all parts of the apparatus operate effectively and automatically, the *registration* of the displacement of the interference fringes being obtained.

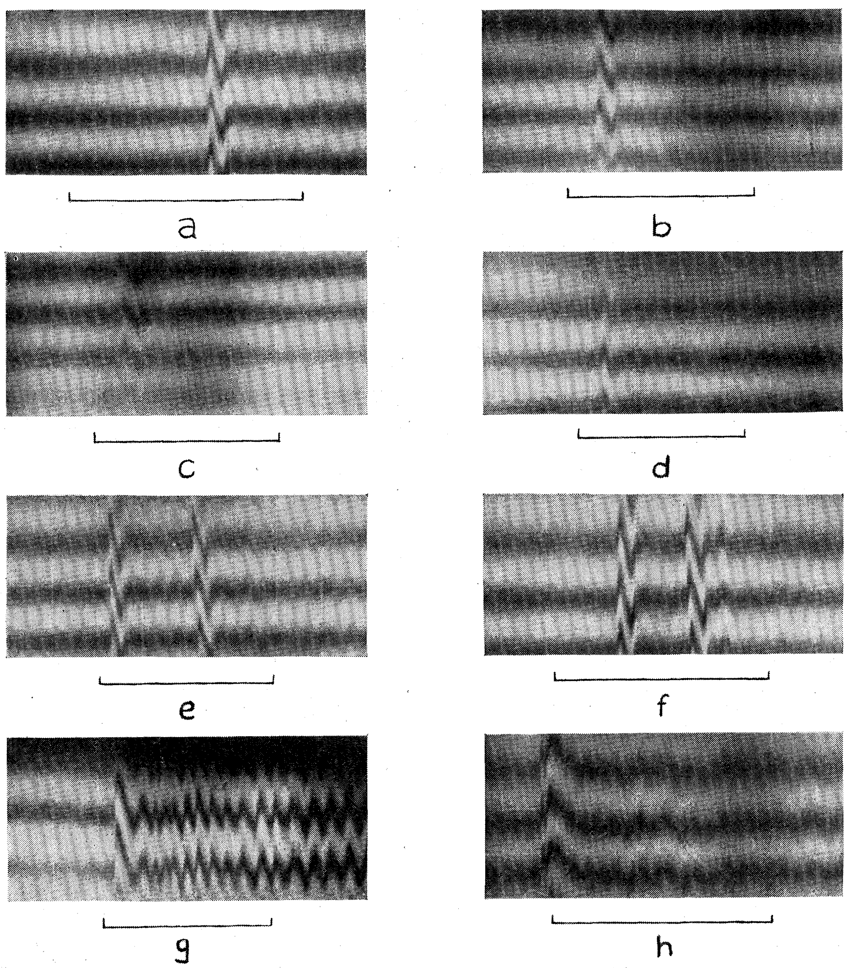

Fig. 3. Displacement of interference fringes obtained by Michelson's interferometer, due to a sound produced by a spark.

In the annexed plate, some of the photographic records obtained are reproduced. The length of the line underneath each photograph represents the time scale of 1/1000 sec. The sense of wave propagation is from right to left. Taking the refractive index of air as *1.00027*, the pressure variation corresponding to the shift of one fringe is about 15 mm of Hg.

Photographs a, b, and c show the variation in the density of the air caused by a wave coming from the sound gap at a distance of 46 cm, 140 cm, and 280 cm, respectively.

Photograph d. Here the sound wave is produced at a distance of 46 cm, but it enters the observing tube after passing through a thin membrane of paper stretched at the end of A. The thickness of the membrane was 0.022 mm and the density was 0.0032 grams per square centimeter. The photograph shows that a strong reflection had taken place as the oscillation was rapid in spite the thinness of the film.

Photographs e and f. In both cases the sound wave was produced at a distance of 46 cm, the left is an advancing wave while the right is one reflected from a hard rubber wall fixed 8 cm and 5 cm apart, respectively, from the observing windows. It will be seen that many small waves follow the main wave, and by adjusting the position of the reflecting surface, the interference takes place between the advancing and the reflected waves as shown in *f*.

Photograph g. In this case, a long wooden tube connecting the whole space between the sound gap and the observing tube was used and the sound wave was produced in this tube. The distance between the sound gap and the observing windows was 100 cm. It will be seen that owing to the repeated reflection of the wave on the inner surface of the tube, many waves caused by these reflections follow the main advancing wave.

Photograph h. Here the wave was also produced in the tube and the gap was placed in a position 32 cm apart from the observing windows. In this case, the inner surface of the tube as far as 22 cm from the gap was covered with a cloth having a thickness of 2 mm in order to absorb the reflected waves. It is remarkable that the record obtained has quite the same appearance as that obtained by S. Garten in his experiment with the soap film, though the wave-length has a different order. We also constructed another tube covered with a sheet of felt 1 cm thick to absorb the reflected waves more perfectly, and got a record, in which the same fine waves appeared as in the former case, but there was not the pressure shift as a whole. It will be interesting to investigate the cause of modification of the wave, but it is not easy to find a satisfactory explanation.

On examining all the records obtained carefully, it will be concluded that, (1) the detonation wave due to a condensed spark discharge is a condensation and not a rarefaction wave. O. Lummer has divided the explosion waves in two classes: (a) the condensation wave due to an explosion of a compact mass (bullet, whip, meteor, explosive materials) (b) the rarefaction wave due to a vacuum excitation (lightning, discharge of a Leyden jar, explosion of a glow lamp), but, in our experiment, the direction of the displacement of the interference fringes is always that of the increasing pressure and the wave must be of a condensation type. The result is in accordance with that found by S. Garten.

(2) The detonation wave is a solitary wave. The wave is in all cases quite a solitary one as shown in the reproductions. This means that the motion of the air at the origin of the disturbance is rapidly damped.

(3) The wave form of the detonation varies as it is propagated onwards. The detonation is a very rapid motion of the air and there results a finite variation of the density. The propagational velocity and the wave-form of the waves having a finite amplitude was a subject of theoretical investigation by Poisson,[17] Riemann,[18] and Lord Rayleigh,[19] and it was concluded that the propagational velocity of the air disturbance is a function of the density of the air and the wave-form varies as the wave proceeds onwards. From the record obtained by us, it will be clearly seen that the period of the oscillation of the air increases with the distance from the origin of the detonation, as shown in Table I, and a sketch showing the variation of the wave-form

TABLE I

Distance	Period
46 cm	1/15000 sec
73	1/13000
140	1/10000
280	1/10000

is also given in Fig. 4. According to L. Foley,[3] at the distance at which we observed, the velocity of the sound wave from a spark has already fallen

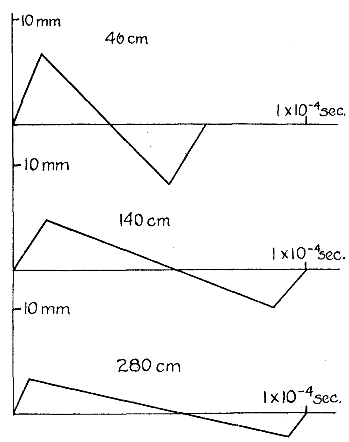

Fig. 4.

nearly to the normal value. Therefore the wave-length increases at the same rate as the wave proceeds onwards.

[17] Poisson, Jour. d. l'ecole Polytechnique VII, 319 (1808).
[18] B. Riemann, Ges. math. Werke p. 165.
[19] Lord Rayleigh, Proc. Roy. Soc. London **A84,** 247 (1910).

It will be interesting to compare our result with others obtained in the case of a detonation due to some other cause. Recently, F. Ritter[20] has observed the variation of the wave-form in the case of the detonation of an explosive material, and he concluded that, (1) the period of positive pressure is smaller than that of the negative pressure, while the absolute value of the pressure variation on the positive side is greater than that on the negative, (2) the amplitude of the pressure variation diminishes and the wave-form approaches gradually to the sine curve as the wave proceeds onwards.

[20] F. Ritter, Beiträge z. Phys. d. freien Atmos. 12, I, (1925).

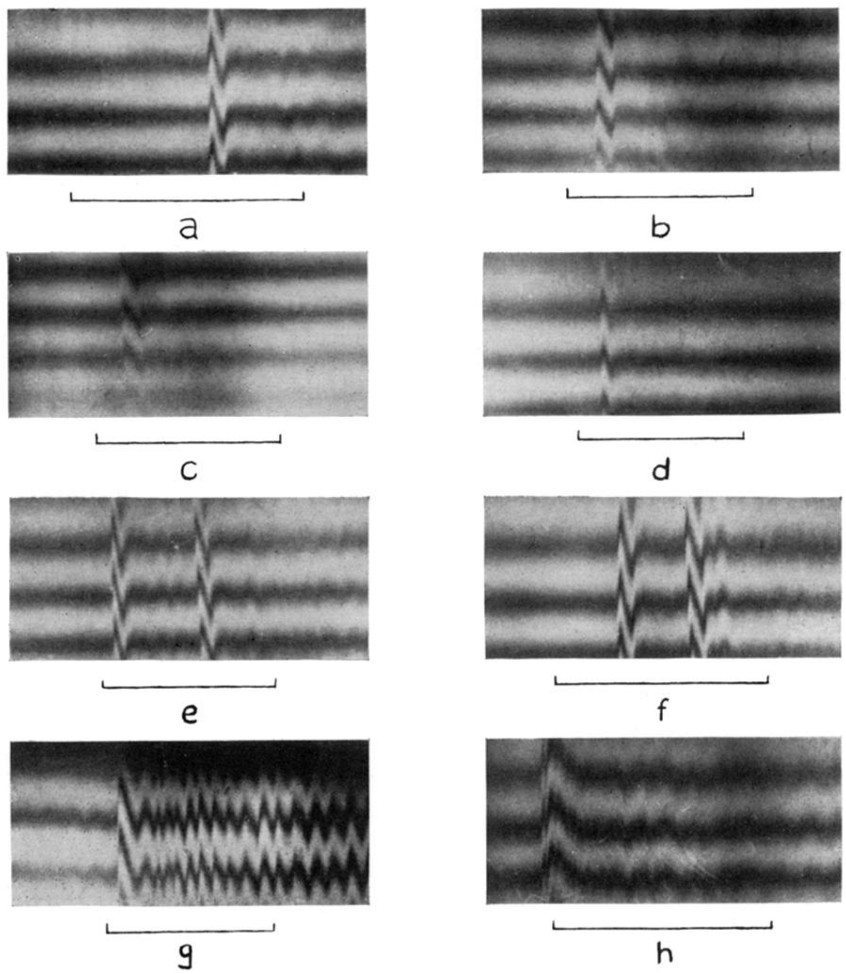

Fig. 3. Displacement of interference fringes obtained by Michelson's interferometer, due to a sound produced by a spark.