OPTICAL STUDIES OF ULTRASONIC FIELDS

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This is to certify that the

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OPTICAL STUDIES

OF

ULTRASONIC FIELDS

by

Glenn G. Lorch

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TABLE OF CONTENTS

INTRODUCTION

Ultrasonic waves are those sound waves which are above the human audible range. Twenty kilocycles is the approximate upper limit for the ear, thus, frequencies above this value are called ultrasonics. Since the frequency is inversely proportional to the wave-length, the wave-length in the audible range will be much longer than, for instance, that used in this paper. Where middle C on the musical scale has a frequency of 256 cycles per second, which corresponds to a wave-length of more than a meter in air, for a frequency of 2 megacycles as used in this work, the wave-length would be less than two-tenths of a millimeter in air. Of course, the velocity of sound in a liquid exceeds that in air, therefore, the wave-lengths obtained in this work will be greater than this value.

There are many advantages in using ultrasonic waves for the determination of the characteristics of sound fields. First, the energy concentration in ultrasonic waves can be very great. Bergmann (6) states that sound intensities greater than 10 watts/cm^2 are common, while in the audible range intensities are of the order of 10^{-10} watts/cm^2. Second, the size of the apparatus can be greatly reduced, since the wave-length of the sound is much less than in the audible range. Thus, the visible field can be many wave-lengths in size while the equipment remains small and easy to handle.

PURPOSE OF RESEARCH

In audible sound fields, the wave-length is of sufficient size that detectors such as microphones are small in comparison, and there is negligible distortion of the field due to their presence. However, for ultrasonic fields, the problem is either to devise a microphone or some other detecting apparatus which is small enough not to distort the sound field, or to find some means by which the field can be investigated without placing a probe or detector in the actual field. A microphone sufficiently small to satisfy the first condition would be considerably less than a millimeter in diameter. At present, no such instrument has been devised. The purpose of this paper is then to discuss optical methods of studying an ultrasonic sound field which allow one to make measurements of the field from a point of observation outside the field.

OPTICAL METHODS

At the present time there are three major methods of making sound fields visible. In 1932, Debye and Sears (8) and also Lucas and Biquard (12), working independently, observed the diffraction of light incident upon a sound field. Thus, the sound field is, in effect, an optical grating. The fundamental laws for an optical phase grating hold for the grating effect of a sound field, and we get the equation

$$\sin \alpha_k = k\lambda/\Lambda \tag{1}$$

where α_k is the angle of diffraction for the k-th order, λ is the wave-length of the incident light, and Λ is the wave-length of the sound. Since the distance D from the sound waves producing diffraction to the point of observation is large compared to d , the distance from the central image to the k-th diffraction image, the value sin α may be replaced by d/D, giving the relationship

$$d = kD\lambda/\Lambda \tag{2}$$

Thus, the position of the diffraction image is directly related to the acoustical wave-length and, therefore, the image separation can be used to determine the velocity of the sound (6). This will be referred to as the diffraction method.

A second important method of rendering sound fields visible is called the Toepler Schlieren Method. In this scheme the incident light from a point source is rendered parallel by a collimating lens and is subject to phase changes due to the variations of optical path in the sound field. Therefore, the light passing through an objective lens placed on the far side of the acoustic trough consists of two parts: that which passes directly through the sound field, and a component which is diffracted by the phase grating characteristics of the sound field and travels from the tank in a diverging manner. The parallel component is brought to a focus by the objective on a circular black spot placed on a glass plate and is not allowed to reach the screen. The diverging component becomes parallel after passing thru the objective and will not be removed by the stop. The intensity variations observed in this diffracted light result from differences in the index of refraction of the medium containing the sound field.

The last method of importance for making sound fields visible is the short-duration spark shadowgraph. This method consists of producing a light source of such short duration that the sound waves are effectively 'stopped'. Such a source is an electric spark produced by the discharge of a pair of co-axial cables across an air-gap. The light from this point source is made parallel by an achromatic lense and passes through the sound field. The differences in density of the medium in the sound field produce variations in the intensity of the light passing through the field. In the more dense regions, the light is partially refracted, producing a darkened area on the photographic plate placed in the light path. Thus, there results an actual reproduction of the sound field.

ULTRASONIC WAVES

TRAVELING WAVES

Let us first consider the traveling sound wave which moves out from the source with a plane wave front. The displacement ξ of this wave will be given by the relation

$$\xi = Y \sin(\omega t - kx - \epsilon) \qquad (3)$$

where Y is the amplitude, ω is the angular frequency, t is the time, x is the position coordinate, ϵ is the phase constant, and k is given by

$$k = 2\pi/\Lambda \qquad (4)$$

where Λ is the wave-length of the sound. Then the excess pressure for the plane harmonic wave will be

$$P = -\rho_0 c^2 \, \partial\xi/\partial x \qquad (5)$$

where ρ_0 is the mean density of the medium, c is the velocity of sound in the medium, and $\partial\xi/\partial x$ is the space rate of change of displacement (5). Now the index of refraction μ for a liquid is given by the expression

$$\frac{(\mu^2-1)}{(\mu^2+2)} \frac{1}{\rho} = n \qquad (6)$$

where n is a constant determined at the known values of density and index of refraction of the liquid (13). For methyl-alcohol, the medium used in this experiment, these constants are given in the literature (9)

$$\mu = 1.3311 \qquad \text{at } 14.5^\circ C$$

$$\rho_0 = 0.79609 \text{ gm/cm}^3 \qquad \text{at } 15^\circ C$$

Thus, the constant n is given by

$$n = 0.2570 \text{ cm}^3/\text{gm}.$$

Now, ρ_0 is the density at conditions of a constant temperature and pressure throughout the medium. However, the introduction of a sound field causes variations in the pressure of the liquid, as seen in equation (5). Since the density is directly related to the pressure, the density at any point in the medium containing a sound field will be

$$\rho = \rho_0 + \delta\rho \qquad (7)$$

where $\delta\rho$ is the change in density due to the sound field or

$$\delta\rho = \delta P/c^2 \qquad (8)$$

In this expression δP is the change in pressure due to the sound field, while c is the velocity of the sound (5).

Combining equations (7) and (8) and placing them in equation (6) gives

$$\frac{(\mu^2-1)}{(\mu^2+2)} = A + B\,\delta P \qquad (9)$$

where, for simplicity,

$$A = n\int_0 \tag{10}$$

and

$$B = \frac{n}{c^2} \tag{11}$$

Then

$$\mu^2 = \frac{[(1+2A) + 2B\delta P]}{[(1-A) - B\delta P]} \tag{12}$$

Factoring (1+ 2A) from the expression in the numerator and (1− A) in the denominator gives

$$\mu^2 = \frac{(2A+1)\left[1 + \frac{2B\delta P}{2A+1}\right]}{(1-A)\left[1 - \frac{B\delta P}{1-A}\right]} \tag{13}$$

Taking the first two terms of the bino mial expansion for $(1 \pm x)^{\frac{1}{2}}$, $(x \ll 1)$, the index of refraction will be

$$\mu = \left(\frac{2A+1}{1-A}\right)^{1/2} \frac{\left[1 + \frac{B\delta P}{2A+1}\right]}{\left[1 - \frac{B\delta P}{2(1-A)}\right]} \tag{14}$$

The higher order terms in the binomial expansion can be neglected, for

$$A = \frac{\mu^2 - 1}{\mu^2 + 2} \tag{15}$$

is always less than one, since μ^2 is always a positive number. From equation (11), B is always a small positive number, therefore, this expression may be written

$$\mu = \left(\frac{1+2A}{1-A}\right)^{1/2}\left[1 + \frac{3B\delta P}{2(1+A)}\right] \tag{16}$$

where again the higher order terms have been neglected. Thus, there is a linear relation existing between the index of refraction and the excess pressure. For the areas of condensation in the sound field, the index of refraction will increase, while there is a decrease in μ for areas in which the pressure is a minimum. Therefore, on the photographs which appear in this paper, the bright areas correspond to regions of condensation.

We have assumed the existence of plane waves in the theoretical treatment. To produce such sound waves, it is necessary to use a source which vibrates in a piston-like fashion. Although there are many possible methods of producing ultrasonic fields, the method most common is the utilization of the piezoelectric effect. In 1880, the brothers Curie found that electric charges could be detected on the surfaces of certain crystals when these crystals were subjected to mechanical pressures or tensions, and that the charge was directly proportional to the pressure. Shortly thereafter, it was shown that this piezoelectric effect was reversible and strong mechanical oscillations could be produced when these crystals were placed in an alternating electric field. However, there are definite polar axes within the crystal. It was found that the maximum charge produced by a mechanical stress on the crystal appeared at the ends of these polar axes (6).

To produce mechanical oscillations, it is necessary to apply a potential difference to the faces of a slab of quartz. If the crystal is cut such that the X axis is perpendicular to the face of the crystal, a charge on this face and an opposite chafge on the back surface will cause the crystal to expand or contract in a piston-fashion as the charges are reversed.

A crystal-controlled pentode oscillator was used to drive the acoustic crystal. This oscillator contained an RK-20A tube which operated with a positive direct current potential of 1000 volts on the plate, 300 volts on the screen grid, and 45 volts on the suppressor grid. The power supply for the oscillator was a full wave rectifier circuit containing two 866 mercury vapor diodes. The tank circuit of the oscillator was connected to a similar exterior tank circuit by means of a link coupling (4). These tank circuits contained a tuning condensor and coil in parallel with a crystal, and care was taken to match their impedences. The control and acoustic crystal were rated at 1806 kilocycles per second. A 0-1 amp. radio frequency ammeter was connected in series with the acoustic crystal. With freshly distilled alcohol, it was possible to pass as high as .4 amperes of current through the external crystal when the circuit was tuned to resonance (the natural frequency of the crystal).

As previously mentioned, the vibrating crystal produces a great deal of power. Thus, if the boundaries of the medium are relatively close to the crystal, very pronounced standing wave patterns are produced. It was necessary to remove these standing wave forms as completely as possible in order to study the traveling waves. This was accomplished by placing layers of cotton cloth at the reflecting boundaries. Surgical gauze was used, since it left very little lint to contaminate the alcohol. Due to its low conductivity, methyl alcohol was used as the medium. This was placed in a trough 6x7x15 cm. so constructed that its two glass sides were as nearly parallel as possible to reduce the reflections between them. These sides were made of plate glass of high optical quality so that the optical defects found in ordinary glass would not be present. The acoustic crystal was suspended at the end of the tank by a bakelite holder on which was mounted a plate of brass. This brass plate served as a backing for the crystal, and was used as one electrode. The acoustic crystal was held in place against this backing by a fork-shaped brass spring which served as the other electrode. A thin layer of gold was evaporated on the two faces of the crystal to ensure a uniform distribution of charge.

To obtain instantaneous spark-shadowgraph pictures of traveling sound waves, it was necessary to develop a circuit which would produce an intense light source of extremely short duration. The velocity of sound in alcohol is given in the literature (6) as 1130 meters per second at 23.8°C., and at a frequency of 1806 kcy/sec., the wave-length is approximately .6 mm. Therefore, the time required for the wave to move one wave-length is about 5×10^{-7} seconds. Thus, to obtain clearly defined instantaneous photographs of the traveling sound wave, it was necessary to expose the film for about one tenth of this time, or 5×10^{-8} seconds. Beams, et al. (3), describe a circuit which meets these requirements. In this circuit, shown in Fig.I, two coaxial cables are discharged across a spark gap. At the moment of arcing, a signal will travel down the transmission line, be reflected from the open end, and return to the gap without a change of phase to act as a damping force on the arc. To obtain a spark of 5×10^{-8} seconds duration, it is necessary to use a cable which is, at most, 25 feet in length. Two 9 foot lengths of transmission line were connected in parallel with the spark gap. A resistor of 52 ohms corresponding to the characteristic impedence of the line was placed in each line in series with the spark gap to completely attenuate the wave. The lines were connected in parallel to increase the total charge without changing the time for the quenching signal to return to the spark gap. The transmission lines were charged with a half-wave rectifier consisting of an 8016 diode, a 12,000 volt transformer, and a 3 megohm resistor to limit the current to less than 4

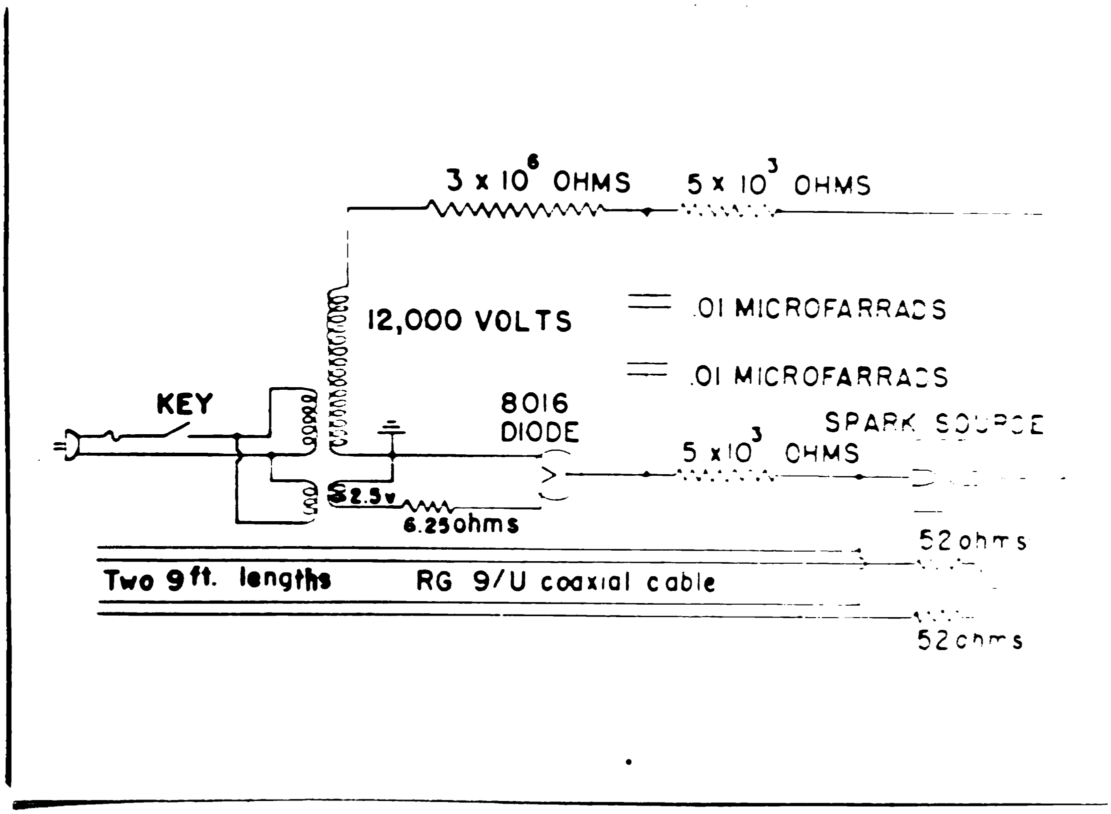

Fig. I Half Wave Rectifier and Spa. . Gap

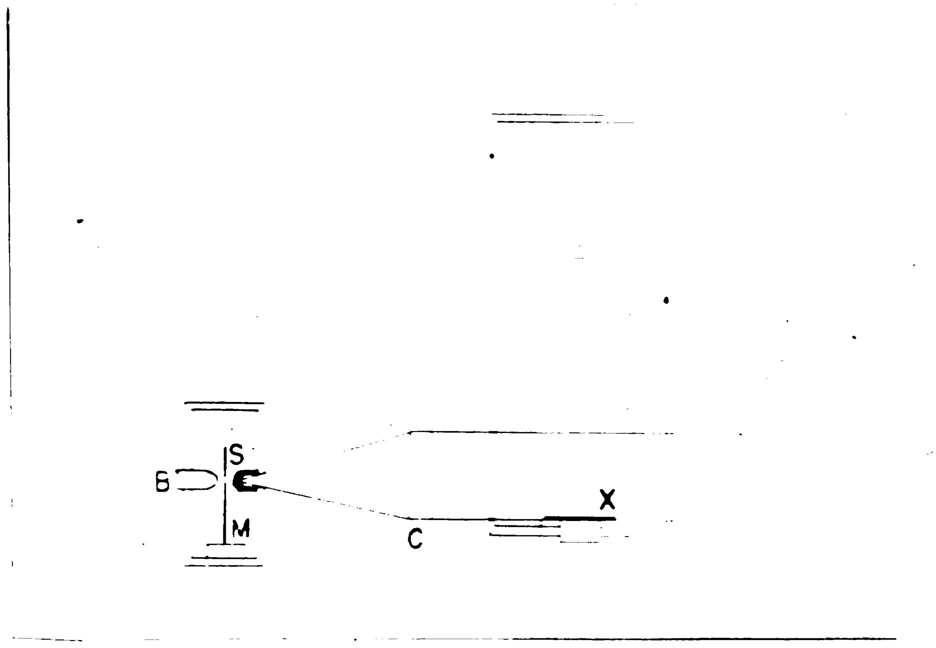

Fig.II Optical Arrangement for Spark Shadowgraph

A. Sound absorber

M. Perforated mica

B. Adjustable electrode

S. Point source electrode

C. Collimating lens

X. Acoustic crystal

P. Photographic plate

milliamperes. The two .01 mfd. condensors connected in series were used to increase the time lapse between discharges, but during each discharge they were effectively isolated from the spark gap by discharging them through the two 5000 ohm resistors. The time lapse between discharges was less than one second for a separation of the spark gap electrodes of 4 mm.; therefore, a key was necessary to control the circuit.

The electrodes were paraboloidal in shape, and one was hollow with a small hole drilled through the end which acted as a point source of light. A great deal of difficulty was encountered in obtaining sufficient light intensity to expose the photographic plates and still keep the length of exposure to the value required. It was found that arcing would occur at various points on the parabolic surfaces of the electrodes; hence, to ensure that the light was available at the hole in the one electrode, a sheet of mica containing a small perforation was placed between the electrodes, which allowed arcing only at the point source.

The schematic representation of the optical system used to obtain spark-shadowgraph pictures is shown in Fig.II. The achromatic lens rendered the light from the point source parallel as it passed through the acoustic trough. A photographic plate was placed at the far side of the field to make a permanent record of the field.

Care was taken that the face of the acoustic crystal was as nearly parallel to the light beam as possible. From equation (5), the pressure varies with the position coordinate, and from equation (16), it is seen that the index of refraction is a function of the pressure, therefore, the bright bands on the positive correspond to areas of condensation. For a traveling wave, the light is diminished at points opposite a rarified region in the sound field. This is plainly evident in Fig. 1.

It will also be noted in Fig.1 that the field is not plane in nature. Further study of this photograph showed that what might be interpreted as two distinct beams inclined at a slight angle towards each other were emanating from the face of the crystal. The product of resonant frequency in kilocycles per second and crystal thickness in millimeters was found to be 1655 indicating an A.T.-cut (7). This particular cut vibrates in a shear mode, giving rise to the unusual character of the field. In Fig.2 an absorber was placed in the sound trough to remove the standing waves. The lines of interference of the two beams transmitted by the crystal are evident in this picture.

Fig.3 is a photograph taken by the Schlieren method. The optical arrangement is shown in Fig.III. The light from a two watt concentrated arc lamp designed as a point source was rendered parallel by an achromatic lens,

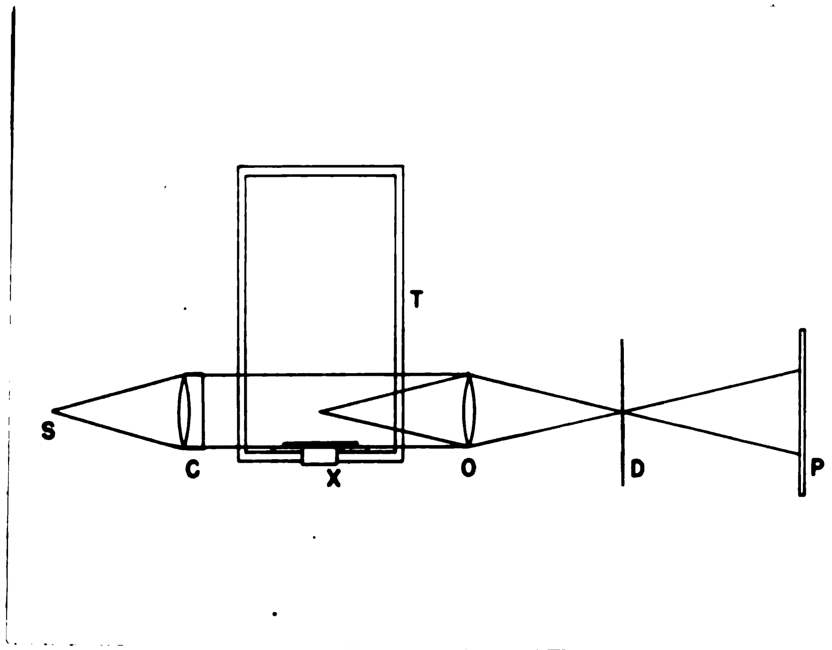

Fig.III Optical Arrangement for Schlieren Photographs

S. Point source

C. Collimating lens

X. Acoustic crystal

O. Objective lens

D. Stop

P. Photographic plate

T. Sound tank

and after passing through the sound trough, was brought to focus on the edge of an aperture cut in a sheet of brass. The central image was removed in this manner, and a dark field was observed at the screen. Now, when a sound field was introduced into the path of the light, this parallel light was 'bent' by the grating effect of the field. While the central image was removed by the edge of the aperture, the higher diffracted orders were allowed to pass through the opening and fall on the screen. Thus, the small aperture acted as a pinhole camera. No mention of this method has been found in the literature. In the common method, as previously described, the central image is removed by a small circular spot, and the higher diffracted orders present at the edge of the spot are brought to focus on the screen by another lense. Since the sound tank was quite small, many reflections from the boundaries of the medium were present which spread out the central image. Therefore, this method proved very unsatisfactory. It must be stated, however, that if a circular aperture is used, extreme caution must be exercised in making the edges of the aperture as smooth as possible to ensure that the central image does not pass through to the screen, for its high intensity will render the higher orders invisible.

Figure 4 is a Schlieren photograph of the sound field with an absorber placed in the trough. Again the possible existance of two inclined sound beams is evident. This photograph was taken of the field at a distance of three centimeters in front of the acoustic crystal. Here, the convergence of these beams is even more apparent than in the spark-shadowgraph pictures. However, since the schlieren method shows only the interference present in the field, the structure of the field is absent.

Figure 5 is a picture of the field with a felt absorber placed over one half of the face of the crystal. It is seen that only a small portion of the interference lines of a beam moving downward from the crystal are present. This further substantiates the existance of a shear vibrational mode in the crystal.

A very simple method of making velocity measurements of ultrasonic fields is available in the diffraction arrangement shown in Fig.IV. As in the previous methods, a parallel beam of light is passed through the sound field, and the areas of condensation and rarifaction combine to act as an optical grating. However, this method differs from those previously discussed in that the point source is now replaced by a narrow slit, and the central image as well as the diffracted orders are viewed at the screen. In equations (1) and (2) it is seen that the wave-length of the incident light must be known to calculate the velocity of the sound. To this end, a green filter was placed between the ribbon-filament, white light source and the collimating lens. The light passing through the tank was then brought to focus on a screen, where the lines of diffraction could be seen. When an absorber is placed in the sound trough, the traveling wave acts as a grating which moves across the light beam with the velocity of the sound. In Fig.6 the diffraction produced by a traveling wave can be seen. In this picture the central image and the first order on either side are visible. To obtain the maximum number of lines and the correct spacing of these lines, the positions of the tank and the lenses are very critical. The objective was a spectacle lens whose focal length was accurately known to be 200cm. This lens was placed at its focal distance from the screen, and then the collimator was adjusted to obtain the sharpest focus possible. Therefore, the light passing through the sound trough was as parallel as possible. With the sound field on, it was found that a very slight rotation of the tank had a marked influence on the number of diffracted orders which could be observed. The maximum number of orders were desired in each case.

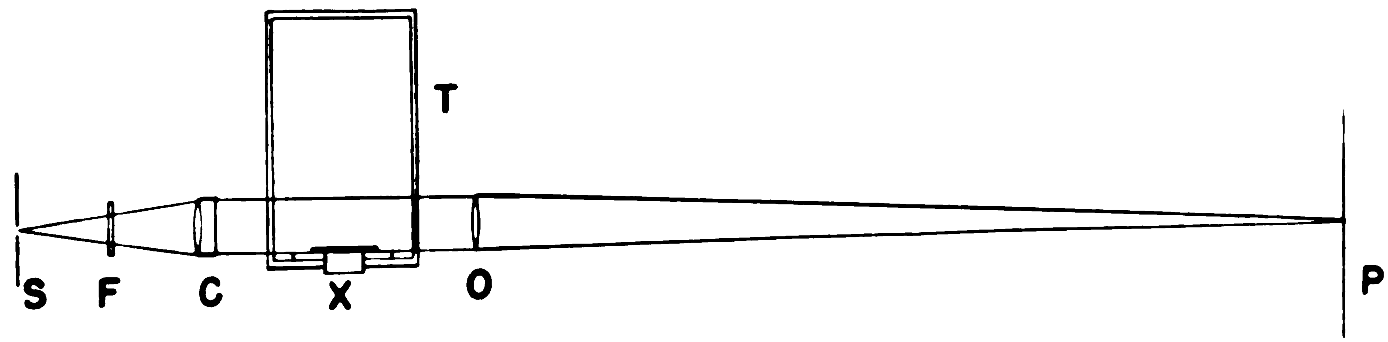

Fig. IV Optical Arrangement for Diffraction Pictures

S. Slit source

F. #62 Wratten green filter

C. Collimating lens

X. Acoustic crystal

O. Objective lens

P. Photographic plate

T. Sound tank

REFLECTED WAVES

From equation (3) it is seen that the displacement ξ of the plane wave is a function of the phase constant ϵ. At a rigid boundary the net displacement of incident and reflected waves must be equal to zero. Therefore, there can be no change in phase between these two waves, and the amplitudes will add. An analogy can be drawn between the ultrasonic field incident on a reflector and a vibrating air column in a closed pipe. For certain positions of the reflector spaced ½ wave-length apart, the displacement and the energy of the sound field is a maximum. For other positions of the reflector, the standing wave will be of smaller amplitude resulting in a decrease in the intensity of the diffracted light. Thus, for sharply defined pictures of standing wave patterns, the position of the source and reflector was very critical, and since the wave-length was less than a millimeter, fine adjustments were difficult to make.

If a long duration spark shadowgraph is taken of a sound field incident on a reflector (see Fig.7), the regions of condensation (appearing as bright lines on the print) occur at half wave-length intervals. However, the instantaneous pictures of the sound field will record the wave in the position assumed at the moment the picture is taken. Therefore, a full wave-length separation will be seen on the photograph, as in Fig.2. By merely taking a long duration and then an instantaneous exposure of the field, the traveling waves can be distinguished from the standing waves by comparison of the two pictures.

In Fig.8 a picture was taken of the crystal oscillating in the sound trough with no absorber present. This was a long duration exposure, and the standing wave patterns visible in the sound field are due to reflections from the boundaries of the tank. Since the distance from the source to the various boundaries was not a constant, the intensity of the diffracted light is seen to vary at different points across the field. Figures 9 and 10 show the same field as Fig.8, but an absorber was introduced into the sound field. In Fig.9 the long duration exposure was used, while in Fig.10 the picture was taken with the instantaneous light source. It is seen that the absorber removes the standing wave patterns, and the instantaneous source renders the traveling wave structure visible.

When a schlieren picture is taken of a field in which the sound beam is incident upon a reflector, the standing wave structure is visible (as in Fig.11), since the parallel light incident on the sound field is diffracted as a result of the variations of pressure. For a traveling wave, these areas of condensation and rarifaction move across the field of view much like a moving optical grating, as previously described. However, for a standing wave, the areas of condensation recur at the same positions in the field giving rise to maximum diffraction of the light from points in the field one half wave-length apart at alternate half cycles. Thus, during the relatively long interval of time in which the schlieren picture is taken, these regions of condensation appear to remain at the same position in the field. The diffracted light from the standing waves will appear as bright and dark bands with the interference effects of the traveling waves in the background. This is clearly evident in Fig.11. A schlieren picture of the field produced with no absorber in the tank again shows the standing wave structure resulting between the source and the boundaries of the tank. (See Fig.8) The interference lines produced by the traveling wave are evident in the background. It should be noted that in each of these pictures the structure of the interference lines of the traveling waves are about what one would expect from two acoustical sources inclined at a slight angle to each other. Here, again, it might be postulated that the field of this crystal consists of two beams moving out from the face of the crystal.

In studying the sound field by the spark shadowgraph and schlieren methods, efforts were made to remove the standing wave forms. However, in making velocity measurements with the diffraction method, it is desirable to have strong standing wave patterns present in the field. This is advisable since the stationary waves exhibit better grating qualities than the traveling wave field due to the higher sound energies existing in the standing waves, and therefore, higher diffracted orders can be observed on the photographic plate. Since more lines are present, a higher degree of accuracy can be obtained in the measurement of the separation of the orders. From equation (2), knowing the distance of the k-th diffraction image from the central image, and having predetermined the distance from the photographic plate to the grating producing diffraction- in this case the sound field- it is possible to determine the velocity c of the sound in the liquid, since

$$c = \Lambda \nu \qquad (17)$$

where ν is the frequency of the sound. For Fig.12 the velocity of sound in methyl alcohol was found to be

$$c = 1223 \text{ m/sec.}$$

This value is slightly greater than the value published in Bergmann (6), but since time did not permit, no attempt was made to reproduce the conditions under which the value given by Bergmann was obtained. Some error would be expected since the wave-length range of the white light source was only limited by a green filter. However, this value does lie in the proper region to be close to the values obtained by other means. If precautions were taken to limit the wave-length of the incident light, and the variations in velocity due to changes in temperature were taken into account, more accurate values should be obtained. It might be mentioned that since this crystal does not vibrate in such a manner as to produce plane waves, erroneous values of velocity might be obtained.

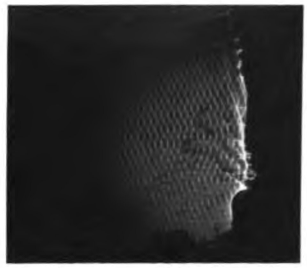

Fig.1. Short-duration sp rk shadowgraph of traveling sound field. The ultrasonic field is produced by an 1806 kilocycle, AT-cut crystal (at right) vibrating in methyl-alcohol.

Fig.2. Spark shadowgraph of traveling ultrasonic waves incident on a sound absorber. Crystal cource is at right.

Fig 3. Schlieren photograph of sound field in medium of methyl -alcohol. Note the standing wave structure present between the source and the tank sides.

Fig. 4. Interference lines of an ultrasonic beam rendered visible by Schlieren method. Source is at right and sound absorber is at left.

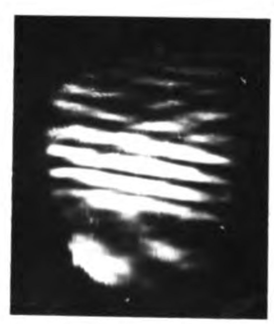

Fig. 5. Schlieren photograph of sound field produced with the lower half of the crystal covered by a mask. This is a picture of the field three centimeters to the right of the crystal.

Fig.6. Diffraction picture of traveling sound waves. A sound absorber has removed the standing wave structure.

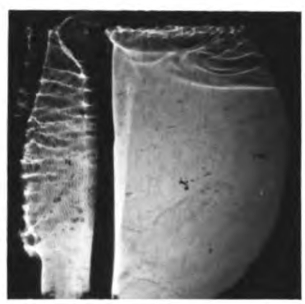

Fig.7. Reflection of ultrasonic beam from brass plate one centimeter from crystal face. This is a long duration spark-shadowgraph.

Fig. 8. Standing waves existing between the crystal face and the boundaries of the medium.

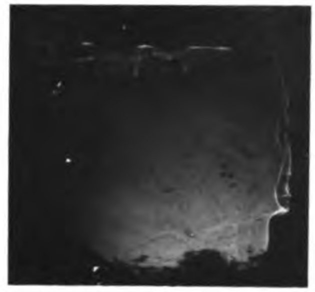

Fig.9. Long duration spark shadowgraph of ultrasonic field in acoustic tank containing sound absorber. Notice that all but a very small portion of the standing wave structure has been removed.

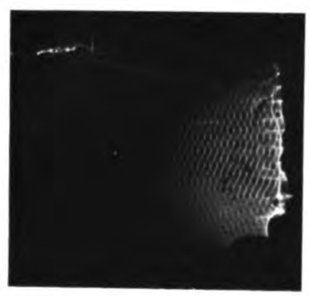

Fig.10. Traveling sound field in a tank containing a sound absorbing material. Exposure time is less than 5×10^{-8} seconds.

Fig.11. Schlieren photograph of ultrasonic beam incident on a brass reflector. Note strong standing wave patterns superimposed on the interference lines. The crystal is located to the left, the reflector to the right.

Fig 12. Diffraction picture of sound field normal to a brass reflector.

CONCLUSION

The problem of obtaining a spark source of sufficiently short duration to 'stop' the traveling wave presented a major obstacle in this study. However, with its solution, it was possible to obtain photographs showing the sound field in great detail. These photographs show clearly the structure of the field, but are of little value in determining the intensity distribution of the sound. Schlieren pictures present little of the structure, but give some indication of the intensity distribution in the field. In each case, however, these pictures show a two dimensional view of a three dimensional field. This, together with the difficulty encountered in going backward from the picture obtained on a photographic plate to the actual field, makes it difficult to obtain a quantitative interpretation of the true nature of the field.

It has been shown that the field produced by an A.T.-cut crystal is quite difficult to analyze, but since this was the only crystal available for this study, an attempt has been made to show the properties exhibited by the field of this crystal. This same crystal was used by Kurtz (11) to measure the velocities of several salts in aqueous solution, and he states, "In adjusting the reflector it was possible to get a good standing wave when the top was one or two wave-lengths ahead or behind the base." This would tend to further establish the existance of two distinct beams leaving the face of the crystal slightly inclined. The field characteristics of this crystal can be compared with the plane wave field of an X-cut crystal by referring to Barnes and Bellinger (1), Hubbard, et al.(10), Barnes and Burton (2), and many other authors who have written on plane sound fields. However, the sound fields of any crystal vibrating in a fluid medium can be studied by the optical methods outlined in this paper. By employing these three methods one can gain insight into the modes of vibration of the crystal and conceivably postulate these modes. The optical methods discussed in this paper have far-reaching application in the study of the diffraction effects of sound waves incident on edges and aperatures. These methods also open a field of study of the interference phenomena produced by crystals inclined at various angles to each other.

Perhaps the most important single conclusion can be drawn from the diffraction data. This method in no way describes the field, the patterns obtained depending only on the wave-length of the sound. It has been long known that this method gives equally good results whether traveling or standing plane waves are produced in the sound cell, but this work indicates that such measurements can also be obtained for more complicated sound fields. The data are insufficient to permit a statement as to accuracy for this last case.

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