MEMOIRS OF THE COLLEGE OF SCIENCE, University of Kyoto, Series A,
Vol. XXVII, No. 1, Article 6, 1953

A NEW METHOD OF MEASURING ULTRASONIC SOUND VELOCITIES IN LIQUIDS

BY

ISAO TAKAHASHI, YOSHIO ISHIDA AND MITSUO ÔTA

(*Received September 7, 1951*)

1. Introduction

It requires a considerable time to measure ultrasonic sound velocities in liquids either by an interferometer (1) or by Debye-Sears's method (2). The present authors have devised a new method by which we can finish the measurement in comparatively short time. The principle of our method is explained. When a train of ultrasonic waves traverses a liquid, it forms a kind of grating against the parallel lights. We will call it an ultrasonic grating. We superpose an optical grating on the ultrasonic grating. Then, no changes occur in the diffraction image when the grid constants of the both two are equal, but if the two grid constants are not equal, the image shows some complication. The difference of images can be clearly recognized. We have ascertained experimentally that when we rotate the optical grating around the light path as the axis, its grid constant varies continuously according to the law: $d = d_0 \operatorname{cosec} \theta$. Therefore, by finding the coincidence of the two grid constants we can know from the rotating angle of the optical grating, the grid constant of the ultrasonic grating, i. e. the wavelength of the ultrasonic wave in the liquid. From this value and the frequency, we can determine the ultrasonic sound velocity.

2. Experimental apparatus

The schematic diagram of the experimental apparatus is shown in Fig. 1.

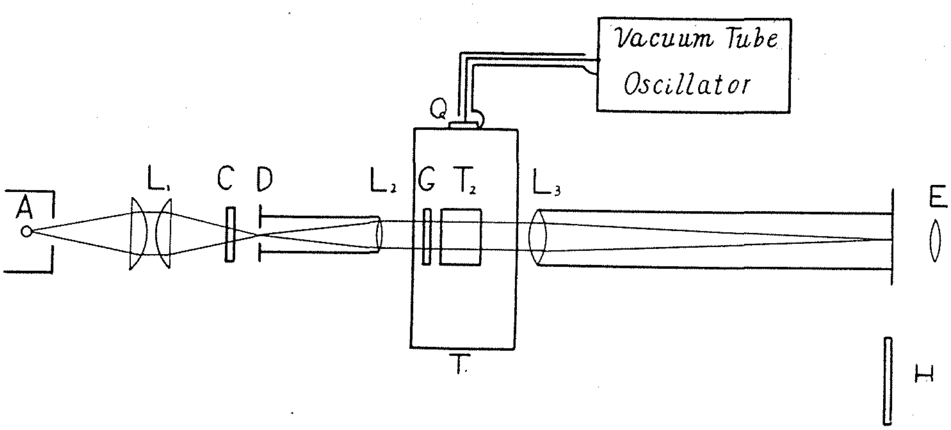

FIG. 1 Experimental apparatus

T_1 : Brass trough containing water, whose both sides consist of polished glasses.
T_2 : Glass trough, which is used to contain liquid samples.
Glass pieces of the trough are connected by melting glass powder of lower melting temperature inserted at their joints. Therefore, it can hold any organic compounds and strong acids.
A : Light source, mercury arc lamp.
L_1 : Condenser lens.
C : Filter which can pass only the green light of mercury spectrum, 5461 Å.
D & L_2, slit and lens respectively, are so adjusted as to make the light rays parallel.
G : Rotatable optical grating, its action being stated later in detail.
Q : Quartz crystal, disk-shaped (diameter 25 mm) cemented over the hole (diameter 12 mm) in one side wall of the brass trough. The resonance frequency 4 Mc/s. It is driven by the vacuum tube oscillator.
L_3 : Image forming lens, the focal length being about 1.80 m. The diffraction image can be observed by an eye-piece E or can be photographed by a plate held in H.

3. Rotatable optical grating

The phenomena when an optical grating is rotated, will be considered here. When the grating is set horizontally, i. e. the lines of grating are perpendicular to the slit, the diffraction image does not appear, excepting a central line. If we rotate it by an angle θ from the horizontal position, the image appears as shown in Fig. 2.

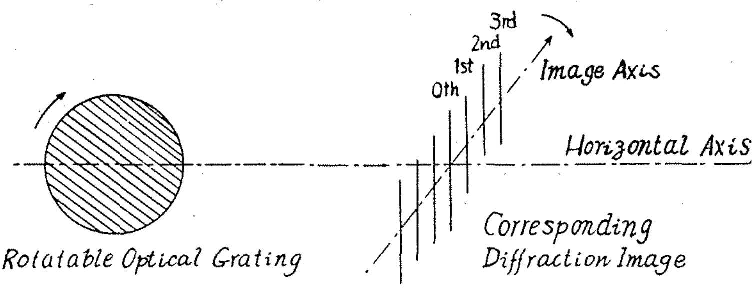

FIG. 2 Effect of rotating the grating

In this case, it is noticeable that the diffraction image consists of vertical bright lines standing in a direction oblique to the horizontal axis. We will call this direction the image axis. When we rotate the optical grating in the sense that θ increases, the inclination of image axis approaches the horizontal line and the distance D between each two lines becomes larger, and at $\theta = 90^\circ$, D becomes maximum.

The formulae for its apparent grid constant at θ can be obtained by a simple geometrical consideration as shown in Fig. 3.

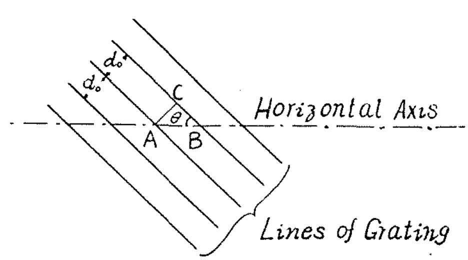

FIG. 3 The consideration for the apparent grid constant

Taking d_0 and d as the original and the apparent grid constant respectively, we get AB = AC cosecθ, i. e.

$$d = d_0 \operatorname{cosec} \theta . \qquad (1)$$

In order to verify experimentally the above relation, we photographed the diffration images corresponding to many rotating angles. From the formula for diffraction grating $\sin\varphi = n\lambda/d$, we get $D_n/L = n\lambda/d$, since φ is small in this case. Here $2D_n$ is the distance between two nth order lines of diffraction image on the photographic plate, and L is the effective distance between the grating and the photographic plate. Therefore, we get

$$d = (D_{n0}/D_n)d_0 , \qquad (2)$$

where D_{n0} means the distance D_n when the apparent grid constant d coincides with the original grid constant d_0.

The grating is rotated by means of a mechanism of worm gear and dial. Thirty-five revolutions of the dial rotate the grating by the angle 90°. Therefore one revolution corresponds to 2.571 degrees. Experimental results are shown in Table I, in which $d_0 = 0.2546$ mm which is directly measured by a comparator.

TABLE I. Apparent grid constants of rotatable optical grating

No. of revolution and corresponding degrees	$2D_1$ (mm)	$d = (D_{10}/D_1)\, d_0$ calculated from the measured value	Theoretical values calculated from $d = d_0 \operatorname{cosec} \theta$
4.5 (11°30′)	1.456	1.360	1.277
7.0 (18°00′)	2.458	0.8060	0.8236
9.5 (24°24′)	3.047	0.6501	0.6161
12.0 (30°54′)	3.886	0.5098	0.4957
14.5 (37°18′)	4.650	0.4260	0.4201
17.0 (43°42′)	5.277	0.3754	0.3685
19.5 (50°48′)	6.005	0.3298	0.3284
24.5 (63°00′)	6.846	0.2893	0.2857
29.5 (76°00′)	7.586	0.2612	0.2623
35.0 (90°00′)	7.781 ($=2D_{10}$)	0.2546	0.2546

Here $2D_1$ is measured by a comparator from the image photographed.

The above data are plotted in Fig. 4. The experimental results and the theoretical values coincide with each other within experimental errors. At the angles smaller than about 12°, the differences between the experimental and theoretical values are comparatively large, but in practice this range of larger error can be avoided by the process which is to be stated in § 5.

4. Procedure of measuring ultrasonic sound velocities

We set a rotatable optical grating perpendicularly to the ultrasonic grating. Then the diffraction image proper to the sample liquid appears as shown in Fig. 5, (A). When we rotate the grating, two lines appear from each original line on its both sides, proceeding in the direction of arrows as shown in Fig. 5, (B), (C) and (D). And when the apparent grid constant of the optical grating coincides with the grid constant of the ultrasonic grating, the image becomes again that as shown in (A).

We have measured by our method the ultrasonic velocities of several liquids.

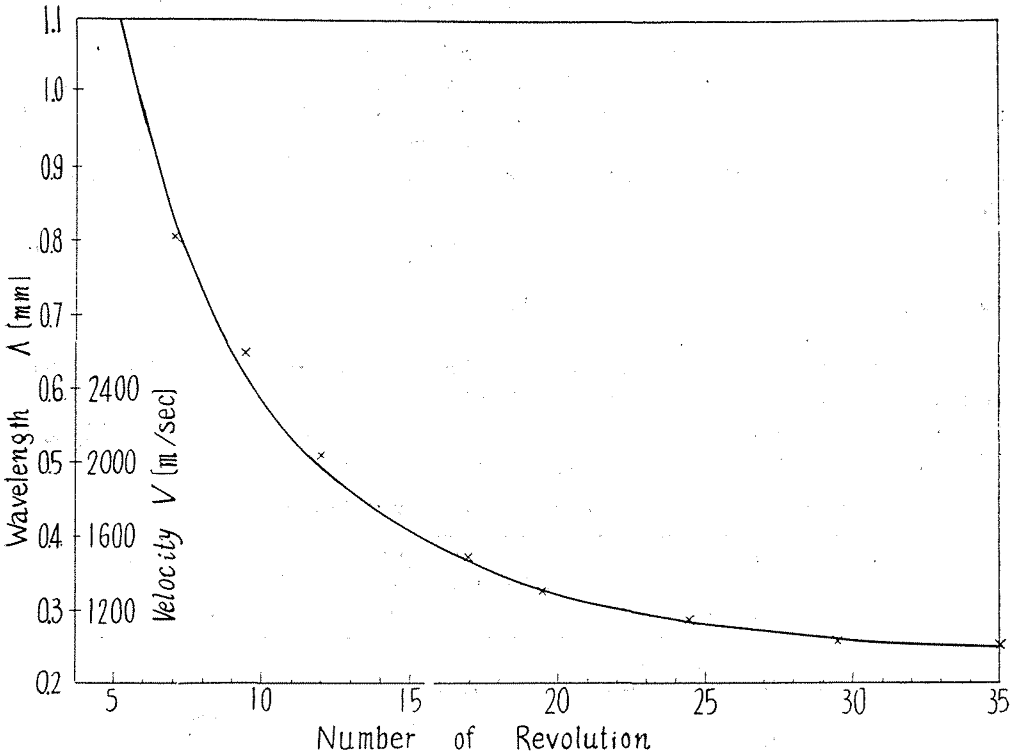

FIG. 4 Relation between wavelength and number of revolution
— Theoretical curve
× Experimental points.

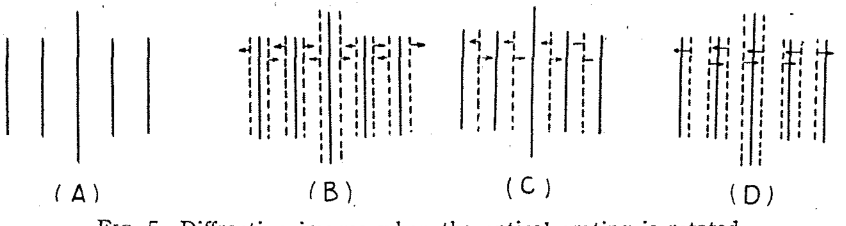

FIG. 5 Diffraction images when the optical grating is rotated.

They are shown in Table II.

TABLE II. Ultrasonic sound velocities measured at frequency 4Mc/s and temperature 30°C.

Liquid	Molecular formulae	No. of Revolution	Column I Λ [mm]	Column I V [m/s]	Column II Λ [mm]	Column II V [m/s]	(1) (2) Ref. data V [m/s]
Water	H_2O	16.24	0.3822	1529	0.3907	1563	1510
Ethyl-alcohol	C_2H_5OH	21.44	0.3103	1241	0.3142	1257	1134
Amyl-alcohol	$C_5H_{11}OH$	22.42	0.3013	1205	0.3062	1225	
Benzene	C_6H_6	20.73	0.3174	1270	0.3198	1280	1276
Ethyl Benzene	$C_6H_5C_2H_5$	20.25	0.3227	1291	0.3237	1295	
Glycerine	$C_3H_5(OH)_3$	11.54	0.5142	2057	0.5356	2142	1905
Chloric acid	HCl	16.52	0.3771	1508	0.3850	1540	
Ethyl ether	$(C_2H_5)_2O$	>35.00	<0.2546	<1018	<0.2546	<1018	949
Chloroform	$CHCl_3$	>35.00	<0.2546	<1018	<0.2546	<1018	967

The values in column I are calculated according to the law $d = d_0 \operatorname{cosec}\theta$, while those in column II, being added for comparison, are obtained by interpolation using the points which have been determined experimentally and are given in the third column of Table I. The samples other than water were not distilled, so that they might contain some impurities which might cause some deviations from the reference data. We could not obtain the values for ethyl-ether and chloroform, because the value of d_0 of the grating which is available for us at present is not sufficiently small. But if we have an adequate grating, we can easily obtain the values of those samples.

The measuring range of our present apparatus begins from 1020 [m/s], but beyond 2000 [m/s] the experimental error becomes large because of the character of cosec θ at smaller θ's. The accuracy of the measurement is 4×10^{-4} at larger angles and 1×10^{-3} at smaller angles.

5. Conclusion

The reliability of this apparatus depends largely upon the rotating mechanism. If it acts satisfactorily, this method is very convenient because the measurement can be performed very speedily. In order to raise the accuracy, it is recommended to divide the measuring range into two parts, namely A (900 m/s~1500 m/s) and B (1400 m/s~2000 m/s) and take adequate values of d_0 for A and B respectively, because we can then avoid the part of cosec θ in which this function changes steeply. For example, against the frequency 4Mc/s, the values $d_0 = 0.2240$ mm for A and $d_0 = 0.3500$ mm for B can be selected.

REFERENCES

1. BERGMANN, *Ultrasonics.*
2. P. DEBYE and F. W. SEARS, 'On the Scattering of Light by Supersonic Waves', *Proc. Nat. Acad. Sci.* **18** (1932), 6.
3. A. WEISSLER, 'Ultrasonic Investigation of Molecular Properties of Liquid', *J. Amer. Chem. Soc.* **71** (1949), 419–421.
4. K. SHIBA, *Butsuri Jôsû Hyô (Tables of Physical Constants).*