# Diffraction of light due to ultrasonic wave propagation in liquids

## 1 Introduction

Acoustic waves in liquids cause density changes with spacing determined by the frequency and the speed of the sound wave. For ultrasonic waves with frequencies in the MHz range, the spacing between the high and low density regions are similar to the spacing used in diffraction gratings. Since these density changes in liquids will cause changes in the index of refraction of the liquid, it can be shown that parallel light passed through the excited liquid will be diffracted much as if it had passed through a grating. The experiment can serve as an indirect method of measuring the velocity of sound in various liquids. The phenomenon of interaction between light and sound waves in a liquid is called the Debye-Sears effect.

## 2 Objective

1. To study the diffraction of light due to propagation of ultrasonic wave in a liquid
2. To determine the speed of sound in various liquids at room temperature
3. To determine the compressibility of the given liquids.

## 3 Theory and evaluation

Diffraction phenomenon similar to those with ordinary ruled grating is observed when Ultrasonic waves traverse through a liquid. The Ultrasonic waves passing through a liquid is an elastic wave in which compressions and rarefactions travel one behind the other spaced regularly apart. The successive separations between two compressions or rarefactions are equal to the wavelength of ultrasonic wave, $\lambda_u$ in the liquid. Due to reflections at the sides of the tank or the container, a stationary wave pattern is obtained with nodes and antinodes at regular intervals. We are thus dealing and hence having a periodically changing index of rarefactions which produces diffraction of light according to the grating rule.

If $\lambda_u$ denotes the wavelength of sound in the liquid, $\lambda$ the wavelength of incident light in air and $\theta_n$ is angle of diffraction of $n$th order, then we have,

$$d \sin \theta_n = n\lambda \tag{1}$$

In a transparent medium, variations in density correspond to variations in the index of refraction and therefore a monochromatic parallel light beam traveling perpendicular to the sound direction is refracted as if it had passed through a diffraction grating of spacing $d$, where $d$ is equal to $\lambda_u$, thus

$$\lambda_u \sin\theta_n = n\lambda \tag{2}$$

If $\nu$ is the frequency of the crystal, the velocity $V_u$ of ultrasonic wave in the liquid is given by,

$$V_u = \nu\lambda \tag{3}$$

Thus, by measuring the angle of diffraction $\theta_n$, the order of diffraction $n$, the wavelength of light, the wavelength of ultrasonic wave in the liquid can be determined and then knowing the frequency of sound wave, its velocity '$V_u$' can be obtained.

## 3.1 Compressibility of liquid

The speed of sound depends on both an inertial property of the medium (to store kinetic energy) and an elastic property (to store potential energy):

$$V_n = \frac{\text{elastic property}}{\text{inertial property}} \tag{4}$$

For a liquid medium, the bulk modulus $\beta$ accounts for the extent to which an element from the medium changes in volume when a pressure is applied:

$$\beta = -V\frac{\Delta p}{\Delta V} \tag{5}$$

Here $\Delta V/V$ is the fractional change in volume produced by change in pressure $\Delta P$. The sign of $\Delta V$ and $\Delta P$ are always opposite. The unit of $\beta$ is Pascal (Pa). Therefore, the speed of sound in liquid can be expressed as

$$V_u = \frac{\nu\lambda n}{\sin\theta} = \sqrt{\frac{\beta}{\rho}} \tag{6}$$

$$\implies \beta = V_u^2\rho = 1/K, \tag{7}$$

where $\beta$ is the bulk modulus of elasticity, $\rho$ is the Density of liquid and $K$ is the compressibility of the liquid

# 4 Apparatus and specifications

### Optical rail

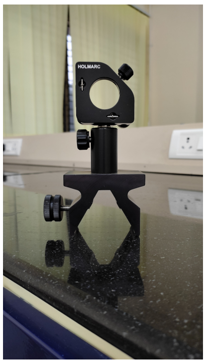
| | |
|---|---|
| **Length** | 2000 mm |
| **Material** | Black anodized aluminium |

### Diode laser with Power Supply

| | |
|---|---|
| **Input** | 230V AC / 50 Hz |
| **Output power** | 3 mW |
| **Wavelength** | 650 nm |
| **Colour** | Red |

### Kinematic Laser Mount

| | |
|---|---|
| **Fine adjustments** | Using 80 tpi lead screws |
| **Adjustment Range** | ±3 degree |
| **Sensitivity** | 20″ |
| **Maximum laser module holder diameter** | 25 mm |
| **Material** | Black anodized aluminium alloy |

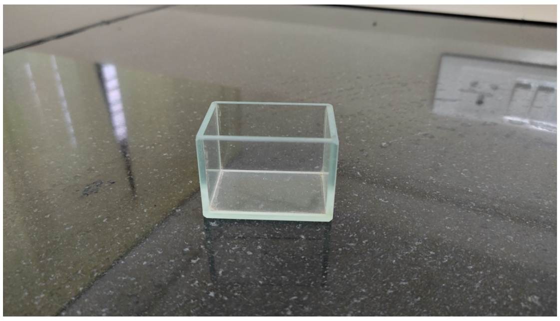


### Glass tank holder

| | |
|---|---|
| **Material** | Black anodized aluminium |
| Can tilt and move, forward and backwards using 80 tpi lead screws | |

### Glass tank

| **Material** | Float glass |
|---|---|
| **Dimension** | 50 mm × 35 mm × 35 mm |
| **Quantity** | 2 Nos. |



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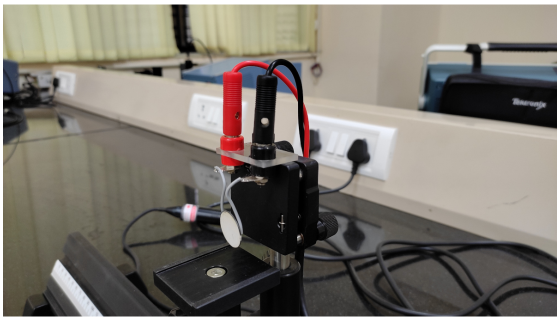
### Piezo Electric Ceramic Disc Transducer



3 MHz crystal

| **Dimension** | 20 mm diameter × 0.7 mm thickness |
|---|---|
| **Resonant frequency, $f_R$** | 3 MHz ± 50 kHz |
| **Resonant impedance, $Z_m$** | ≤ 6 Ω |
| **Static capacitance $C_s$** | 5700 pF ± 15 % at 1 kHz |

5 MHz crystal

| **Dimension** | 20 mm diameter × 0.7 mm thickness |
|---|---|
| **Resonant frequency, $f_R$** | 5 MHz ± 100 kHz |
| **Resonant impedance, $Z_m$** | ≤ 0.48 Ω |
| **Static capacitance $C_s$** | 3800 pF ± 20 % at 60 Hz/V |

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### RF oscillator

| **Frequency range** | 2 MHz - 6 MHz |
|---|---|
| **Input** | 230 V / 50 Hz |

# 5 Procedure

1. Make the basic adjustment of the setup.
   (a) Fix the kinematic LASER mount on one end of the rail. Fix the glass tank holder in the middle of the optical rail so that it is close to the kinematic laser mount. Fix the detector mount at the other end of the optical rail.
   (b) Insert and fix the photodetector in the detector mount and connect the cable to the output measuring unit.
   (c) Insert and fix the LASER diode in the kinematic laser mount and make sure that the cable is not on the rail or it is not causing any obstruction.
   (d) Fill the glass tank with the liquid under test and place it on the glass tank holder. Immerse the crystal oscillator in the liquid and fix it on the holder. Connect the crystal to the RF oscillator using the connection wires.
   (e) Switch on the LASER. Use the kinematic set up to align the laser so that its beam is parallel to the phase of the crystal and the beam falls at the center of the pin-hole photodetector.
2. Switch on the RF oscillator and adjust the frequency according to the crystal used, if it is the 3 MHz crystal, apply 3 MHz (diffraction occurs when the frequency applied to the crystal becomes equal to the resonance frequency or natural frequency of the crystal.)
3. Observe the diffraction pattern on either sides of the central bright spot on the detector.
4. Using the micrometer driven translation stage, move the detector to any of the extreme ends of the diffraction pattern.
5. Scan the pattern at specific intervals say 0.5 mm of the micrometer and note the corresponding detector output. Wait at each interval for a few seconds so that the output stabilizes for taking the reading.

# 6 Calculation of least count of the micrometer

Length of the smallest main scale division of the micrometer $l_s$=
Distance $h$ travelled by the micrometer in $q$ rotations =
Pitch of the micrometer screw $p = h/q$ =
Zero error $z_E$ = Number of divisions of the circular scale of the micrometer $N_{CS}$=

Least count of the micrometer $LC = \dfrac{p}{N_{CS}} =$

Total reading is given by $TR = MSR + CSR \times LC$, where $MSR$ is the main scale reading, $CSR$ is the circular scale reading and $LC$ is the least count.

# 7 Observations

Wavelength of the laser $\lambda$ = 650 nm
Distance between the crystal and the detector =
Frequency of the crystal = Density of liquid =

**Table 1:** Observation from pin-hole photo detector.

| Micrometer reading (mm) | Detector output ($\mu$A) |
|---|---|
| | |

**Table 2:** Calculation from graph.

| Order $n$ | Distance from the central spot to the $n^{\text{th}}$ order spot D (m) | | | Angle of ultrasonic diffraction $\theta = \arctan(D/L)$ | $\Lambda = n\lambda/\sin\theta$ (m) | $V = \nu\lambda$ ($\mathrm{m\,s^{-1}}$) |
|---|---|---|---|---|---|---|
| | On Left | On Right | Mean (m) | | | |
| | | | | | | |

# 8 Results and Discussion

1. Report the mean velocity in each of the liquids.
2. Calculate the Bulk modulus of Elasticity and compressibility for each liquid
3. Estimate the experimental errors, both relative and propagation error.
4. Compare the results with data from literature.

## Literature values for speed of sound

# 9 Precautions

1. Rotate the knob on the RF oscillator extremely slowly to vary the frequency.

| **Medium / material** | **Speed** ($\mathrm{m\,s^{-1}}$) | **Reference** |
|---|---|---|
| Water | 1493 | [1] |
| Kerosene | 1324 | |
| Turpentine oil | 1240 | |

2. The crystal should be mounted parallel to the side walls, otherwise a good standing wave pattern will not be obtained and hence diffraction grating will not be formed. As a result the higher orders may not be of equal intensity on either side of maxima.

## Note

1. Velocity of sound in liquids is temperature dependent.

2. From this experiment we are determining the bulk modulus for adiabatic compression because there is no energy exchanged with the region next to the sound wave. This should be distinguished from the isothermal bulk modulus.

# References

[1] Online. URL: `http://www.engineeringtoolbox.com/sound-speed-liquids-d_715.html`.

[2] *Ultrasonic diffraction, Model: HO-ED-A-01, Instruction Manual*. Holmarc Opto-Mechantronics Ltd.