Diffraction of light due to ultrasonic wave propagation in liquids

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.

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.

Apparatus:

1. Radio frequency oscillator fitted with a frequency meter
2. Quartz crystal slab fitted with two leads
3. Spectrometer
4. Glass cell with sample liquid (kerosene/Toluene/Turpentine oil etc)
5. Sodium lamp
6. Spirit level.

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, λ_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 λ_u denotes the wavelength of sound in the liquid, λ the wavelength of incident light in air and θ_n is angle of diffraction of n^{th} order, then we have,

$$d \sin \theta_n = n\lambda$$

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 =λu, Where d is equal to λ_u, thus-

$$\lambda_u \sin \theta_n = n\lambda$$

If ν is the frequency of the crystal, the velocity 'V_u' of ultrasonic wave in the liquid is given by,

$$V_u = \nu \lambda_u$$

Thus, by measuring the angle of diffraction θ_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.

Compressibility of liquid, K

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):

$$V_u = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

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

$$B = -\frac{\Delta p}{\frac{\Delta V}{V}}$$

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

$$V_u = \frac{\nu\lambda n}{\sin\theta} = \sqrt{\frac{E}{\rho}}$$

$$\Rightarrow E = V_u^{\,2}\rho = 1/K$$

Where, E = Bulk modulus of Elasticity
ρ = Density of liquid.
K= the compressibility of the liquid

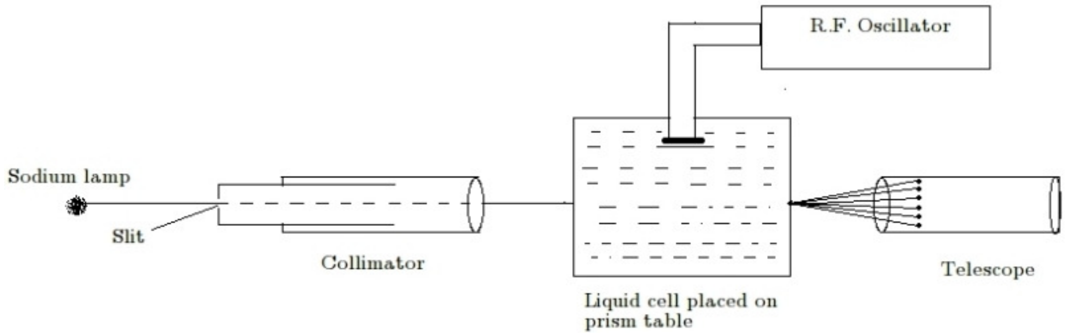

Figure 1: The schematic of the ultrasonic diffraction experiment

Procedure:

1. Switch on the sodium vapor lamp (if it is not on) and wait for 15 minutes to get the intense light.
2. Check for basic adjustment of the spectrometer. If needed level it taking help of the support manual for the spectrometer.
3. Place the glass cell containing the experimental liquid (i.e. kerosene oil or others) on the central part of the prism table.
4. Mount the transducer (quartz crystal in its holder) and dip it exactly parallel in the liquid near a wall of the glass cell so that the ultrasonic waves produced by the crystal travel in the liquid in a direction perpendicular to that of the incident light. Connect the leads of the transducer with the output terminals of the RF Oscillator.
5. See through the telescope eyepiece so that a sharp well defined image of the slit is seen in the field of view in the centre of the micrometer scale fitted in the eyepiece.

6. Now switch on the RF Oscillator. Adjust the frequency of the Oscillator to generate the ultrasonic wave (of the order of ~2MHz) so that it becomes equal to the natural frequency of the crystal slab. At this stage resonance takes place and diffraction images of the slit will be seen in the telescope. Note the frequency of the RF Oscillator and maintain it constant throughout the experiment.
7. Using the vernier scale on the angle display window, measure the angles corresponding to m = 0, m = ±1 and m = ±2. Use the data to find out the wavelength of the sodium light.

Observations:

Least Count of Spectrometer = ________
Frequency of Vibrating crystal = ________
Density of liquid = ________

Table: (Make separate tables for different liquids)

Order	Left of Central		Right of Central		2θ = (a –b)	**2θ = (a′-b′)**	Average 2θ	θ	V_u (m/s)
	a	a′	b	b′					
Set-I 2^{nd} order 1^{st} order									
Set-II 2^{nd} order 1^{st} order									
Set-III 2^{nd} order 1^{st} order									

Order	V_u (m/s)			Mean V_u (m/s)
	Set-I	Set-II	Set-III	
1^{st} order				
2^{nd} order				

Sample result for turpentine oil is 1237.8 m/s

Reported value[1] of the mean velocity of ultrasonic wave in turpentine is 1240m/s at room temperature.

Results and Discussion:

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

Precautions:

1. Rotate the knob on the RF oscillator extremely slowly to vary the frequency.
2. This experiment requires precision in taking readings, especially the minutes in the spectrometer scale.
3. The crystal should be mounted parallel to the side walls, otherwise a good standing wave pattern will not be obtained & hence diffraction grating will not be formed. As a result the higher orders may not be of equal intensity on either side of maxima.

Reference:

1. http://www.engineeringtoolbox.com/sound-speed-liquids-d_715.html

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.*