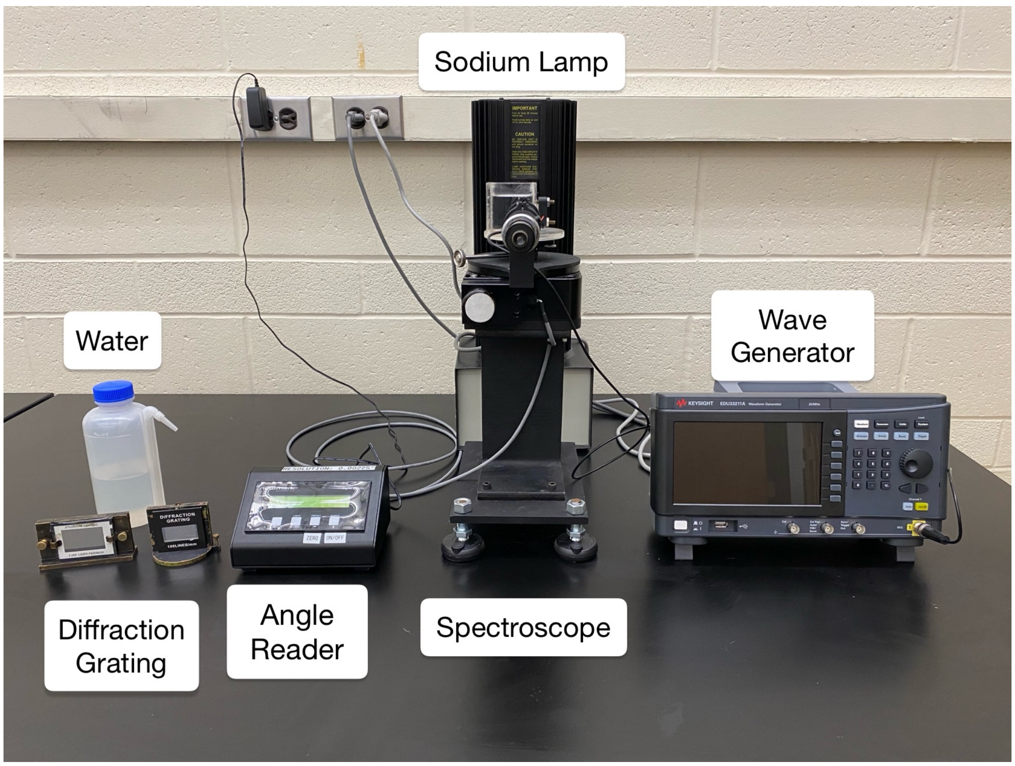
Physics
UNIVERSITY OF TORONTO

The velocity of Ultrasonic Waves in Water by the Debye-Sears Effect



Revisions

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Introduction

This experiment uses an ultrasonic standing wave in water as an optical diffraction grating. You will study the diffraction of light through density fluctuations of water. You will measure the speed of sound in water and will determine the bulk modulus of water.

Theoretical background

The Debye-Sears Effect

Sound waves in liquids propagate by changing the density and pressure in the nodes and antinodes. The spacing of the antinodes, the wavelength, is determined by the frequency f_s of the wave and by the propagation speed v_s.

In a transparent medium like water, these variations in density affect the index of refraction of the medium and affect the propagation of light travelling through. This effect is maximized if the light travels perpendicularly through the sound waves that behave as a diffraction grating where the wavelength of the sound wave determines the spacing of the diffraction grating.

Light passing through a diffraction grating is diffracted at an angle that depends on the grating spacing d and the wavelength of light λ as $\lambda = d \sin\theta$. This effect repeats at many angles, satisfying the equation

$$m\lambda = dsin\theta. \tag{1}$$

where m is the order of diffraction, θ is the angle of each diffraction order from the origin, and λ is the wavelength of the light source.

speed of sound and bulb modulus of water

Sound waves in water are expected to have a linear dependence on the frequency of the sound waves, related to the speed of sound propagation

$$v_s = f_s\lambda_s \tag{2}$$

where v_s is the speed of sound, f_s and λ_s are the frequency and wavelength of the sound waves, respectively.

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

$$v_s = \sqrt{\frac{B}{\rho}}, \tag{3}$$

where ρ is the density of water and B is the *Bulk Modulus* in Pascal. The Bulk Modulus accounts for the relative change in volume of the medium when a pressure is applied: $B = -\frac{\Delta p}{\frac{\Delta V}{V}}$.

The Experiment

Exercise 1

In order to gain some familiarity with diffraction measurements, the spectrometer should be set up with the standard diffraction grating provided for the first experiment.

Switch on the Sodium lamp and let it warm up for at least 10 minutes. It will start as a red-coloured light and become yellower as it warms up. The yellow light is the familiar Sodium lamp colour we want for this experiment.

Place the diffraction grating on the rotating temple in between the two telescope tubes. Adjust the setup so that you can see two thin yellow lines separated by a narrow gap in the telescope eyepiece. You may see a rotated cross-hair in the eyepiece to help with alignment, but parallax effects are significant in the setup and need to be considered in your measurements.

Slowly rotate the viewing telescope until you see higher diffraction orders.($m = \pm 1, 2 \ldots$). Using the digital angle reader, measure the angles between each diffraction order. You might see as high as $m = \pm 5$ in a dark room. Use this data, along with equation 1 to find the wavelength of the Sodium lamp. In this setup, the diffraction grating separation depends on the grating you use, which may be listed as a line density instead of a line spacing (e.g. "2500 lines per inch").

> Note that the digital angle reader provides a measurement in degrees with a resolution of 0.00225°. You might need to press *Preset* or *Zero* to start the measurements of θ. You should also check the effect of parallax on your data by repeating the measurement of the angles.

Once you have calculated the wavelength of the Sodium lamp, compare it to the literature values for the standard emission lines of Sodium in the visible wavelengths.

Exercise 2

To measure the speed of sound in water, you will use a small water cell connected to an ultrasonic transducer. The KEYSIGHT EDU33211A signal generator drives the transducer to produce a standing acoustic wave in the water cell. This water tank appears as a (fuzzy) diffraction grating to the light from the Sodium lamp and you can measure the wavelength of the water waves by treating it as a diffraction grating in equation 1. Fill the cell with the provided water and replace the fixed diffraction grating with the water cell. Adjust the instrument as needed to get a sharp image of the light in the telescope.

The KEYSIGHT EDU33211A is a signal generator with accuracy in the range of one part per million[1]. The frequency values you set in the signal generator can be taken as the measurement of the sound frequency in the water cell.

Switch on the signal generator and check the output frequency. By default, it should start at around 1.7MHz, but you can adjust it as needed through the `sine wave` settings

[1] it is more accurate than most of our oscilloscopes

and then through the `frequency` settings. The output voltage should be on the order of 10V.

This experiment's challenge is finding the value of v_s in equation **??**. To find this speed, you need to measure the wavelength and frequency of the water wave. For some values of generator frequency, you should be able to set up a standing water wave with a fixed wavelength that can be treated as the diffraction grating in equation 1. You should measure multiple frequencies from around 1.7MHz to 2.1MHz to calculate a more accurate speed f_s.

Using your frequency and wavelength measurements of the water waves, plot λ_s against $1/f_s$ and calculate the speed of sound in water v_s and bulk modulus of water B. Confirm whether the relationship between wavelength and frequency is linear as predicted by equation **??** - a non-linear relationship would be evidence that sound waves are dispersive in water (e.g.,`https://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-further-dispersive.htm`)

Compare your results with data from the literature on the speed of sound in water and whether water is dispersive or not.

> The speed of sound in many liquids is known to be temperature-dependent. The lab temperature should be consistent throughout a single session but might vary depending on the outside temperature

References

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