University of Toronto
ADVANCED PHYSICS LABORATORY

SONO

Sonoluminescence

Revisions
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Please send any corrections, comments, or suggestions to the professor currently supervising this experiment, the author of the most recent revision above, or the Advanced Physics Lab Coordinator.

Introduction

Sonoluminescence is the production of light by sound [1, 2]. Since sound quanta (phonons) have energies about 11 orders of magnitude lower than light quanta (photons), converting sound to light is a complex collective phenomena involving fluid mechanics, physical chemistry, thermodynamics, quantum mechanics, and plasma physics.

In this experiment you will be studying single bubble sonoluminescence, where light is produced by an acoustically driven oscillating microscopic gas bubble in a liquid.

Sonoluminescence was first discovered in 1933 as a faint glow when many bubbles are produced by cavitation. Single bubble sonoluminescence was discovered in 1962, and again in 1970, and again in 1990. This last rediscovery established reproducible methods for single bubble sonoluminescence, creating an explosion of interest because the phenomenon is easily accessible, is not well understood [2, 3], and has potentially interesting applications.

In addition to sonoluminescence, the physics of acoustic bubbles [4] is in itself a complex phenomena of great interest that can be investigated in this experiment.

Theory

Multibubble sononoluminescence occurs when many bubbles are produced by ultrasonic driven cavitation. In this case the ultrasound both produces the bubbles and drives their oscillations which produce sonoluminescent bursts of light. In single bubble sonoluminescence, production of the bubbles and the sonoluminescence are separate processes. The bubble can be produced by various processes, e.g. boiling, injection of gas into the liquid. A standing acoustic wave is then used to both trap the bubble and drive the bubbles oscillations.

Acoustic Cells [5]

This experiment uses one or both of two acoustic cells, one rectangular and one cylindrical. The cell is filled with liquid and ultrasonic standing waves set up. In a rectangular cell with rigid walls of dimensions (L_x, L_y, L_z), standing wave resonances will occur when the frequency of the ultrasound is given by

$$f_{lmn} = \frac{c}{2}\left[\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2\right]^{1/2} \tag{1}$$

where c is the speed of sound in the liquid, and (l, m, n) are the integer mode numbers. At these eigenfrequencies, the pressure within the cell as a function of time and position within the cell will be given by

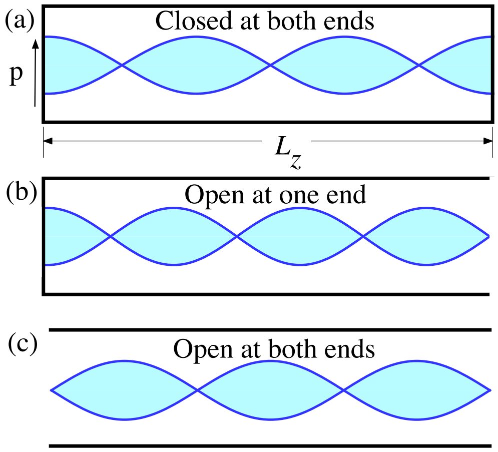

Figure 1: Cell pressure along z-axis depending on whether the cell is (a) closed, (b) open at one end, or (c) open at both ends.

$$p_{lmn}(x, y, z, t) = p_0 \cos\left(\frac{l\pi x}{L_x}\right)\cos\left(\frac{m\pi y}{L_y}\right)\cos\left(\frac{n\pi z}{L_z}\right)\cos\left(2\pi f_{lmn} t\right) \tag{2}$$

The $p_{113}(0,0,z,0)$ pressure profile for $x,y,t=0$ is shown in Figure 1(a). Figures 1(b) and (c) show the profiles for if one or both ends of the cell are open and the liquid fills all space, corresponding to obvious modifications of Equation 2.

A vertical cylindrical cell of radius R_c and height L_z has eigenfrequencies and eigenmodes:

$$f_{lmn} = \frac{c}{2}\left[\left(\frac{\nu_{lm}}{\pi R_c}\right)^2 + \left(\frac{n}{L_z}\right)^2\right]^{1/2} \tag{3}$$

$$p_{lmn}(x,y,z,t) = p_0 J_l\left(\nu_{lm}\frac{r}{R_c}\right)\cos(l\phi)\cos\left(\frac{n\pi z}{L_z}\right)\cos(2\pi f_{lmn}t) \tag{4}$$

where J_l is the lth order Bessel function.

Bubble oscillations

A gas bubble in a liquid can oscillate in many ways, but the dynamics of a spherically symmetric gas bubble in liquid are reasonably well described by the Rayleigh-Plesset equation[1]:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left[\left(p_0 + \frac{2\sigma}{R_0} - p_\mathrm{v}\right)\left(\frac{R_0}{R}\right)^{3\kappa} + p_\mathrm{v} - \frac{2\sigma}{R} + \frac{4\eta\dot{R}}{R} - p_0 + P(t)\right] \tag{5}$$

where ρ is the liquid density, p_0 is the hydrostatic pressure in the liquid at the location of the bubble, R_0 is the equilibrium bubble radius, κ is the polytropic index for the gas, and σ and η are the surface tension and kinematic viscosity of the liquid. $P(t)$ is the time-varying pressure due to the ultrasound. Under adiabatic conditions, $\kappa = \gamma = c_p/c_v$ (the ratio of specific heat at constant pressure to the specific heat at constant volume for the gas in the bubble). The first terms on the right-hand side of Eq. 5 represent the expanding force due to the gas pressure inside the bubble:

$$p_i = p_g + p_\mathrm{v} = \left(p_0 + \frac{2\sigma}{R_0} - p_\mathrm{v}\right)\left(\frac{R_0}{R}\right)^{3\kappa} + p_\mathrm{v} \tag{6}$$

where p_v is the vapour pressure of the liquid and p_g is the pressure of any other gas inside the bubble. The next two terms in Eq. 5 parameterize the effect of surface tension which tries to contract the bubble, and the effect of viscosity which resists any change in the bubble size.

The simplest radial "breathing" mode of the bubble has a resonant frequency[2]

$$f_r = \left[\frac{3\gamma p_{i,e}}{\rho R_0^2} - \frac{2\sigma}{\rho R_0^3} + \frac{\omega^2(\omega R_0/c)^2}{1+(\omega R_0/c)^2}\right]^{1/2} \tag{7}$$

where $p_{i,e}$ is the equilibrium pressure or the gas inside the bubble, and ω is the radial frequency ($\omega = 2\pi f_d$) of any ultrasound driving the oscillations.[3] For a typical undriven air bubble in water, the first term in the above equation dominates, and after inserting appropriate numerical values it reduces to

$$f_r \approx \frac{3\ \mathrm{m/s}}{a} \tag{8}$$

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[1] Ref. [4]:Eq.4.81, or Ref.[2]:Eq. 1.14 (but note that the sign of the last term in Eq. 1.14 has a typo).

[2] Ref. [4]:Eq.4.199.

[3] The corresponding equation on p.89 of Ref. [2] differs slightly because it uses p_0 instead of $p_{i,e}$. For the bubble to exist in equilibrium, $p_{i,e} > p_0$. See Equations 3.204 and 2.8 of Ref. [4].

This means that for a given acoustic driving frequency, the resonant bubble radius is

$$a_r \approx \frac{3\text{ m/s}}{f_d} \tag{9}$$

so at 30kHz the resonant radius is 100μm. A typical sonoluminescence bubble is 10 to 100 times smaller than this.

Bubble Trapping[4]

Bubbles in a standing wave in the cell are subject to acoustic radiation pressure *Bjerknes forces* that push bubbles towards or away from pressure nodes and antinodes. The primary Bjerknes force in the vertical (z) direction in our cell is[5]

$$F = 2\pi R_0^2 n \xi_0 \sin 2nz P_A \cos\alpha \tag{10}$$

where $\xi_0 \sin 2nz$ is the amplitude of the radial oscillations of the bubble driven by the standing wave pressure oscillations

$$P(t) = p_0 + 2P_A \cos(\omega t + \alpha). \tag{11}$$

$\omega = 2\pi f$, and $\alpha = 0/\pi$ for bubbles smaller/larger than the resonant bubble radius.

Bubbles smaller than the resonant radius are repelled by pressure nodes and attracted to antinodes, while the reverse is true for larger bubbles.

Bubble Collapse

Solving the Rayleigh-Plesset Equation (Eq. 5) is not simple. A numerical solution[6] for a typical sonoluminescent bubble is shown in Ref. [2] Fig. 3.28. A bubble initially has radius of about 6μm and an internal pressure equal to atmospheric pressure (10^5Pa). As the applied pressure from the ultrasound standing wave goes negative, the pressure of the gas within the bubble causes the bubble radius to expand by ~ 10, and the pressure within the bubble falls by two orders of magnitude. (The pressure doesn't fall three orders of magnitude because the number of gas molecules within the bubble increases by ~ 10 due to molecules vaporizing from the liquid.) Once the ultrasound pressure goes positive, the bubble starts to collapse to almost zero radius, and the gas pressure and temperature within the bubble spikes to $\sim 10^{10}$Pa ($\sim 10^5$ atmospheres) and $\sim 10^4$K. The bubble oscillations then decay away before the process begins anew with the next standing wave cycle.

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[4] See Ref. [2], Sec. 1.3.7

[5] Ref. [2]:Eq.1.28 or Ref. [4]:Eq.4.150 with with V_0 eliminated; using n instead of k for the vertical mode wavenumber.

[6] Originally from Yasui, K. (1997), *Alternative model of single-bubble sonoluminescence*, Physical Review E, **56**, 6750-6760; doi:10.1103/PhysRevE.56.6750.

Experiment

Safety Reminders

- Any vessel that is going to be evacuated with a vacuum pump must be vacuum rated and undamaged. Inspect the Erlenmeyer flask for cracks or chips before using.
- Be sure to read the MSDS (Material Safety Data Sheets) for any chemicals you may use other than water. The lab technologists can provide MSDS for any chemicals you obtain from them, or you can look them up at http://ccinfoweb.ccohs.ca/msds/search.html.
- Check with the supervising professor before using any liquid other than pure distilled water in the cell.
- Only use liquids that are easily water soluble. e.g. no oils.
- Do not fill the cell with a flammable liquid, e.g. water with a few percent alcohol is okay, but not more.
- Keep any flammable liquids away from the electronics and electrical wiring. In particular, do not spill any alcohol inside the box or leave an alcohol container inside the box. (Calculating how much spilled alcohol it takes to create an explosive mixture when the box is closed is an interesting theoretical exercise, but we don't want to find out experimentally.)
- Do not press the heater switch if the heater coil is not attached and immersed in water. The heater power supply produces potentially dangerous currents and the heater coil will melt if turned on in air.
- Do not touch any live electrical leads, or accidentally short them out.
- Be careful not to drop the box door on your head or fingers (or anyone else's).

NOTE: This is not a complete list of all possible hazards; we cannot warn against creative stupidities, e.g. juggling cryostats. Experimenters must use common sense to assess and avoid risks, e.g. never open plugged-in electrical equipment, watch for sharp edges, . If you are unsure whether something is safe, ask the supervising professor, the lab technologist, or the lab coordinator. If an accident or incident happens, you must let us know. More safety information is available at http://www.ehs.utoronto.ca/resources.htm.

To easily observe sonoluminescence requires the right depth of cold, mostly degassed, distilled water in a clean acoustic cell driven with moderate ultrasound amplitude precisely at resonance. A temperature of $< 5^\circ$ C and an oxygen level of $\sim 2-3\,$mg/L are good starting values for the water. These values should be reached in about 25-45 minutes pumping on about 500 mL of distilled water in a 1 L Erlenmeyer flask sitting in an ice water bath on the magnetic stirrer.

Before starting the experiment, watch the short quick-start video and become aware of the other information available at http://www.physics.utoronto.ca/~phy326/sono and the Appendices here.

Warnings, Hints, & Suggestions

- The cell may have more than one acoustic resonance peak, so you need to scan around to make sure you are on the highest amplitude one.

- Sonoluminescence only occurs if there some, but not too much, dissolved gas.

- Don't put too much force on the cell, e.g. by jamming in an ice pack too forcefully, or you may crack the glue holding the cell to the base.

- There are two hydrophones: The fixed one at the bottom of the cell is normally used. The rod hydrophone can be used to measure the acoustic signal at any point inside the water, e.g. to map up the nodes and antinodes directly.

- Once the cold degassed water is poured into the rectangular cell to a depth of $\sim 11\,\text{cm}$, use one or two ice packs to keep the cell cold. The ice packs can be adjusted or removed to study the temperature dependence of the sonoluminescence. Don't forget that if the water temperature changes, so will the resonance frequency.

Bubbles

- The bubbles that produce sonoluminescence are too small to see with the unaided eye. Bigger bubbles can be interesting for other reasons, e.g. studying the Bjerknes forces on bubbles in standing acoustic waves.

- If the peak acoustic pressure is too low, sonoluminescence will not occur because the right sized bubbles may not be trapped or the collapse is not strong enough to produce light. If the peak pressure is too high, sonoluminescence will also not occur, e.g. because the trapped bubbles may be destroyed (i.e. dissolved) before there is time for light to be produced.

- An alternate way to create bubbles is to extract a bit of water from the cell with a syringe or eyedropper, and then to drop the water back into the cell.

- The oscillations of bubbles in the water can by seen on the hydrophone output, see Fig. 2.

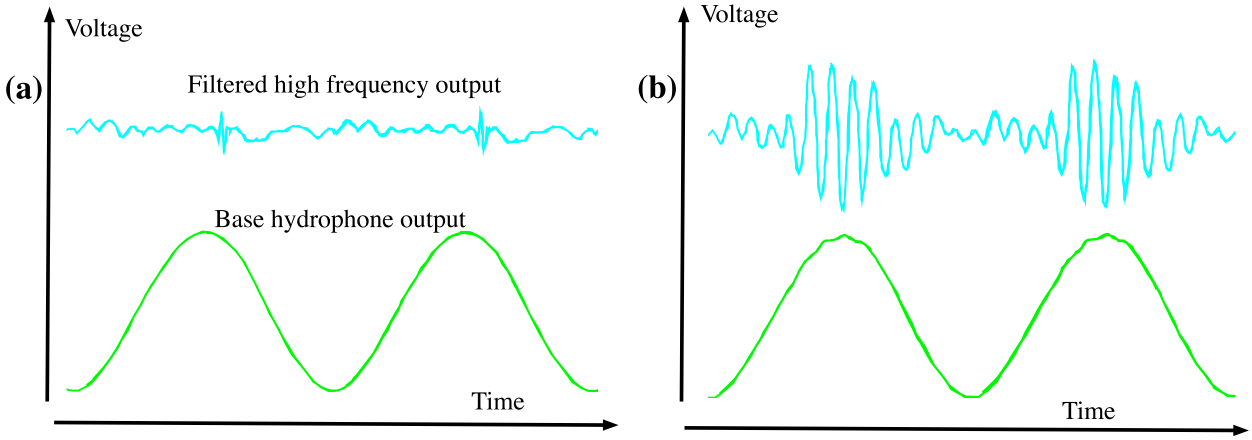

Figure 2: Base hydrophone signal without (a) and with (b) a trapped sonoluminescent bubble. The bottom curve is the raw signal from the hydrophone; the upper curve is the signal after the SL100B high frequency filter.

Cleanliness

- Keep dust, lint, and other particles out of the water, unless you intentionally want to study how particles are trapped at nodes or antinodes. An antinode with a trapped dust mote will not trap bubbles.

- Don't let the flask stopper touch the floor. Any dirt picked up by the stopper could fall into the distilled water.
- Clean the cell and horn carefully after using anything other than pure water. Marks will be deducted if a professor notices that you've left a dirty cell for the next student.

Oxygen Probe

- The oxygen probe tip has a membrane that will break if it ever completely drys out, so keep the cap on the Oxygen probe when it is not in use, or the probe may die.
- This type of dissolved oxygen probe only works if water is moving over its tip. The magnetic stirrer keeps the water moving over the tip when measuring in the flask, but to measure the oxygen level of the still water in the acoustic cell, the probe should be gentle moved up and down a bit in the water.

Photomultiplier Tube (PMT)

- **Be sure the Photomultiplier Tube is turned off before opening the light-tight box.** Exposing the powered PMT to room light could destroy it. Cover the PMT when not in use for long periods.
- The PMT pulse rate should not depend on whether the room lights are on or off. If it does, repack the black cloth and paper around the holes where the wires pass through the side of the box.

Questions

- What are the vertical positions of the antinodes in the cell? Are they where you expected them to be? Is the surface of the water equivalent to an open or closed cell boundary, or neither?
- What is the Q value for the cell resonances which you used to observe sonoluminescence?
- Can you use Eq. 9 to estimate the size of the sonoluminescent bubbles from the high-frequency acoustic oscillations observed on top of the driving ultrasound signal? This can be done by feeding the hydrophone signal into the SL100B and looking at the high-frequency output, or possibly by using the Fast-Fourier Transform function directly on the oscilloscope.

Possible Investigations

Sonoluminescence

- How does SL intensity depend on temperature [6], ultrasound amplitude, or dissolved gas level?
- Can sonoluminescence be observed at difference modes and frequencies?
- Can sonoluminescence be observed in the cylindrical cell? Is the rectangular or cylindrical cell better, worse, or the same for producing sonoluminescence?
- How does sonoluminescence depend on adding soluble chemicals to the water? [7, 8] Such chemicals can change properties such as the surface tension, viscosity, vapour pressure and density of the liquid, all of which appear in the Rayleigh-Plesset Equation (Eq. 5).
- Does the phase of the SL flash relative to the driving ultrasound shift as you vary the ultrasound intensity, temperature or other parameters? For a long-lived bubble under constant conditions, does the phase (or other parameters) drift with time?

- What is the relationship between the size and frequency of the bubble oscillations observed on the high-frequency output and the amplitude of the sonoluminescent light?

Advanced

- What is the spectrum of the sonoluminescent light? Can the colour be usefully observed with the experiment's new macro video camera? Is it a thermal spectrum, and if yes, what is the temperature? What is the temperature of the sonoluminescent bubble? (The York University Advanced Physics Lab has a nice discussion about how their students investigate the spectrum: http://physwiki.apps01.yorku.ca/index.php?title=Main_Page/PHYS_4210/Sonoluminescence.
- How does sonoluminescence depend on the type dissolved gases in the water? Bubbling argon or nitrogen through the distilled water before cooling and degassing should remove the dissolved air. The oxygen meter can be used to confirm that the ambient air has been (presumably) replaced by the introduced gas.
- Is it possible to produce and observe multibubble sonoluminescence?

Acoustics and Bubbles

- Why are there two resonant frequencies close together near 28kHz in the rectangular cell?
- How do the cell modes (i.e. antinode positions, resonant frequency, node amplitudes) depend on the height of the water, depth of horn below the surface? How many different resonant modes can you see?
- How does the measured cell resonance frequency for pure water depend on temperature? Is this consistent with the literature values for the speed of sound in water as a function of temperature inserted into Eq. 13?

Advanced

- What can you learn about the physics of oscillating bubbles?
- Can the size of the bubbles in the cell be measured? The effect of bubble size on sonoluminescence could then be studied, and the oscillations of known size bubbles could be used to calibrate both the rod and bottom hydrophones [9]. The experiment has a new macro video camera, which should allow size measurement of sufficiently large bubbles. What counts as "sufficiently large" is unknown. Using a laser to illuminate the bubbles and measuring the scattering is another possible way.
- If the bubble sizes can be determined, then it would be interesting to study the trapping forces on the bubbles, e.g by measuring the position of the bubbles as a function of ultrasound frequency, amplitude, and bubble size.

References

(Electronic versions, if available, are accessible by clicking on the title.)

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Appendices

A Quick Start Video

A 13 minute video showing how to produce your first sonoluminescence signal with our apparatus: https://www.youtube.com/watch?v=KBR6oz4X4h8

B SL100B Instructions

Information on the apparatus, instructions, and suggested experiments are available from the manufacturer at http://www.sonoluminescence.com

C RCA 931-A Photomultiplier Tube Specifications

Available at http://pdf.datasheetarchive.com/indexerfiles/Scans-008/Scans-00177374.pdf

D Possibly useful practical formulae

The saturation concentration (mg/L) of dissolved oxygen in pure water at 5°C is S=12.77 mg/L (and 8.74 mg/L at 22°C). Its value as a function of absolute temperature (T in Kelvin) is approximately [10]

$$S = e^{-139.34410+1.575701\times10^{5}/T-6.642308\times10^{7}/T^{2}+1.243800\times10^{10}/T^{3}-8.621949\times10^{11}/T^{4}} \tag{12}$$

accurate to better than 0.1% over the temperature range 0-40°C.
(Plot available at http://docs.engineeringtoolbox.com/documents/639/oxygen-solubility-water-2.png.)

The speed of sound (m/s) in pure water at 5°C is $c = 1426.2$m/s. Its value as a function of temperature (T in °C) is approximately [11]

$$\begin{aligned} c = 1402.385 + 5.038813\,T - 5.799136\times10^{-2}\,T^{2} + 3.287156\times10^{-4}\,T^{3} \\ -1.398845\times10^{-6}\,T^{4} + 2.787860\times10^{-9}\,T^{5} \end{aligned} \tag{13}$$

accurate to ±0.03m/s in the temperature range 0-75°C.
(Plot available at https://commons.wikimedia.org/wiki/File:Speed_of_sound_in_water.svg.)

The surface tension (N/m) of pure water at 5°C is $\sigma = 0.07495\,\mathrm{N/m}$. Its value as a function of absolute temperature (T in Kelvin) is approximately [13]

$$\sigma = 0.2358\left(1-\frac{T}{T_c}\right)^{1.256}\left[1-0.625\left(1-\frac{T}{T_c}\right)\right] \tag{14}$$

where $T_c = 647.15\,\mathrm{K}$, accurate to better than 1% over the temperature range 0-185°C. (Plot available at https://upload.wikimedia.org/wikipedia/commons/d/d8/Temperature_dependence_surface_tension_of_water.svg.)

The diffusion constant (cm^2/s) of oxygen in pure water at 5°C is $D = 1.14\times10^{-5}\,\mathrm{cm^2/s}$). Its value as a function of absolute temperature (T in Kelvin) is approximately [12]

$$D = 10^{-4.410+773.8/T-(506.4/T)^{2})} \tag{15}$$

accurate to a few % over the temperature range 0-95°C.