Sonoluminescence establishment
Projet en autonomie 3P024

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(Dated: April 24, 2017)

This article deal with sonoluminescence and its establishment for an undergraduate project. First, we'll see theory behind this phenomenon (what we currently know), then we'll describe the protocol and achievements to reproduce it and our results.

Introduction

In acoustic, we can generate waves which is not propagate in space under special constraints (fixed extrema of string under specific frequencies for example). We call them standing waves.

If we consider ultrasound waves (> 20 kHz) into a liquid, with a sufficient intensity we can trap bubble(s) in node or antinode, one for the basic mode and more for other modes.

Then, under conditions developped later, this (or these) bubble(s) can implose and deliver light! This is what is called *sonoluminescence* (SL). We'll distinguich two cases: multi-bubble sonoluminescence (MBSL) and single-bubble sonoluminescence (SBSL).

Although currently we can't explain why this light is emitted, but we can explain the dynamics of bubble. This is what we take as our first part, then we'll describe our experiment.

Briefs elements of theory

Dynamic description of bubble: cavitation and fluid pressure field [1]

To understand the bubble motion on fluid and especially its implosion, we have to call out fluid mechanics arguments (Rayleigh-Plesset equation). Indeed, the bubble implosion is due to cavitation phenomenon.

We are going to explain this. Also, we'll have to say why bubble is (or are) trapped in the fluid.

Rayleigh-Plesset equation

When we talk about bubble motion, we actually talk about of *radius* bubble motion. Indeed, as we describe previously, the bubble is standing on fluid.

Let the following Navier-Stokes equation [2]

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\vec{\nabla}\vec{v}\right) = -\vec{\nabla}p + \vec{\nabla}\cdot\boldsymbol{T} + \boldsymbol{f} \qquad (1)$$

With ρ the fluid density, $\vec{v}$ the fluid velocity, p the pressure, $\boldsymbol{T}$ the stress deviator tensor and $\boldsymbol{f}$ the force density tensor.

So, it is assumed that from Eq.1 can be derivated the Rayleigh-Plesset differential equation [2],[3],[4]

$$\rho\left(R\ddot{R} + \frac{3}{2}\dot{R}^2\right) = [p_g(R,t) - P_0 - P(t)] - 4\mu\frac{\dot{R}}{R} - 2\frac{\sigma}{R} + \frac{R}{c}\frac{\partial p_g}{\partial t} \qquad (2)$$

With ρ the density of liquid, R the bubble radius, p_g the pressure in bubble, P_0 pressure far from bubble, $P(t)$ the driving pressure, μ the shear viscosity of liquid, σ the surface tension at interface and c the speed of sound in liquid.

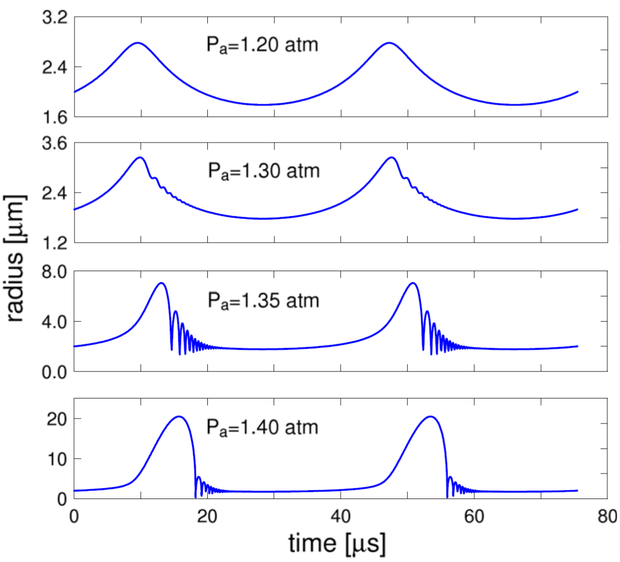


FIG. 1: Representation of different solutions for the Eq.2 at 26.5 kHz [5]

We clearly see (Fig.1) non-linear solution for the highest pressures.

Also, we can have an idea of SL duration and magnitude, and we see that the phenomenon presents some cycles (two periods represented) of the order of a few dozen µs each.

We also note that the radius can increase its size by a factor of about ten around µm. [3]

Thus, these data give us an idea of difficulties and challenges of observation.

Bubble position: Bjerknes forces [2]

To successfully trap a bubble, it is necessary to have an inhomegenous pressure field: a pressure gradient $\vec{\nabla}p$.

In the general case, under these different pressures, we have the Archimede's principle who acts on the bubble's surface S :

$$\vec{F} = -\oiint_S p \, \mathrm{d}\sigma = -\iiint_V \tilde{\nabla} \mathrm{p} \, \mathrm{d}\tau$$

In the SL case, the volume V of bubble oscillates at the ultrasound wave frequency and $\vec{\nabla}p$ reverses every half of period.

Since the acoustic wavelenght is much bigger than bubble's lenght, we can consider an homogenous gradient around the bubble, so we have $\vec{F} = -4\pi R^3(t)\vec{\nabla}p$. It's the *Bjeknes* force.

Then, we assume that $\langle\vec{F}\rangle$ is directed to the center of anti-node because of the pressure extremum (Fig2). So, obviously in the case of SBSL at basic state of resonance in circular flask, the bubble is at the center of the sphere.

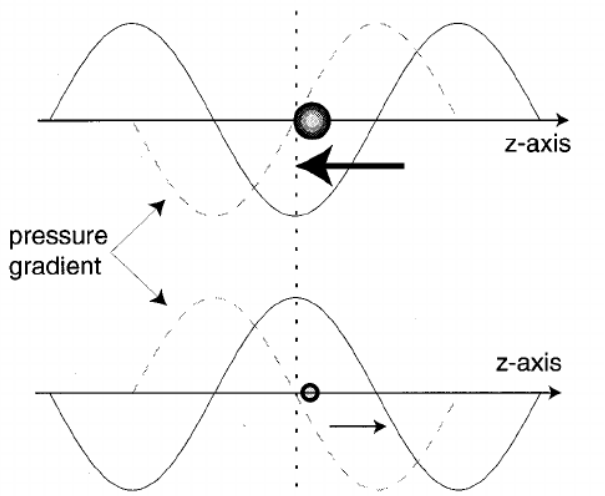


FIG. 2: Schema of bubble position finding under Bjerknes forces

The pressure field has to be strong enough to have a powerful radius oscillation and, finally, light emission.

Also, in a perfect case, we hope to have SBSL at basic mode to have the bubble at the center of the sphere.

But as we will see, it's an experimental challenge to have this ideal case because of material and conditions of the experiment.

Flask resonance

Thus, we will develop here the flask's resonance conditions and criticize them.

In this experiment, we'll use a spherical flask, and we associate form to a sphere of radius r. The dissipative effects are not taken into account.

Here, we use the d'Alembert formula for surpressure p:

$$\Box p = 0 \tag{3}$$

Where $\Box$ is the d'Alembert operator $\Box = \frac{1}{v^2}\frac{\partial^2}{\partial t^2} - \Delta$

We consider here the laplacian Δ in spherical coordinates applied to a function f:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial f}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\phi^2}=0$$

So with these considerations, 3 become:

$$\begin{aligned}&\frac{1}{v^2}\frac{\partial^2}{\partial t^2} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial p}{\partial r}\right)\\&+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial p}{\partial\theta}\right)\\&+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 p}{\partial\phi^2}=0\end{aligned} \tag{4}$$

From this equation, we assume that the solution take this form [3]:

$$p(r,\theta,\phi,t) = p_0 J_l(kr) P_m^l\left(\cos\theta\sin\left(m\phi\right)\right)e^{i\omega t}$$

Where l and m are integers, J the Bessel function and P the Legendre polynomials. The exponential term is a phase term. Here, we are interested by the module of p.

We immediately see that there are many solutions that describe different modes.

We search solutions for $p = 0$, that's mean solutions associated to anti-nodes. In basic modes, we have $l = m = 0$ so Legendre polynomials are equal to 1 and Bessel function is equal to sinc (kR), where sinc is the sinus cardinal function and k the wave number $k = \frac{\omega}{v}$ neglecting dissipation. Plus, in using edge conditions we can deduce the condition sinc $\left(\frac{\omega R}{v}\right) = 0$

$$\begin{aligned}&\operatorname{sinc}\left(\frac{\omega R}{v}\right) = 0\\&\Rightarrow \frac{\omega R}{v} = \pi m\\&\Rightarrow \omega = \frac{v\pi}{r}m\end{aligned}$$

With $m \in \mathbb{N}$. Thus:

$$f_{l=0} = \frac{v}{2R}n$$

Finally, we can deduce the first resonance modes by expressing R in term of V (sphere volume, 100mL in our case) and with v the wave velocity in water at 18°C, $v = 1470$m/s, we have:

$$\begin{aligned} f_{l=0,n=1} &= 25.695\text{kHz} \\ f_{l=0,n=2} &= 51.390\text{kHz} \\ f_{l=0,n=3} &= 77.085\text{kHz} \\ f_{l=0,n=4} &= 102.780\text{kHz} \end{aligned} \quad (5)$$

However, those frequencies change very fast with the temperature, we learn it from J.-L. THOMAS, who worked on SL ([6]) and here the main challenge is to keep a stable temperature [4].

It's quite difficult because the ultrasound transmitters heat up the mixture, so we have to find a way to keep the water stable and cool[4][7].

Stable because we want a high Q factor, and cool because SL is very sensitive to temperature. Typically to see better the SL we have to be under ≈ 20°C, the more we can go down, the more we can see the light from the bubble.

Also, we briefly can mention the influence of type of mixture used in SL.

For example, with different liquids (sulfuric acid for example [8]) or with different gases, especially noble gases like Argon, Krypton or Xenon [8],[7],[9], we can influence the brightness and the color of light into the bubble.

Experiment [10]

Protocol and apparatus

Flask

Even if this experiment doesn't require a lot of hardware, the main difficulty for this project was to found ultrasound transmitters and receivers, as we'll develop below.

For the flask, according to the previous calculations Eq.4 and solutions 5, we need a spherical flask (useful geometry) in glass.

For the volume, we've chosen a 100 mL flask because its resonance modes are in ultrasound range frequencies, so more comfortable to work. Thanks to chemistry department for the loan of this flask.

Electronic components

To have a sufficient pressure, we need more power than the usual current from the lab, so we need an current amplifier.

For this experiment, our supervisor Q. GLORIEUX loan us a basic hand made speed amplifier, but without numerical gain values on it ($\approx \times 1000$ max.)(Fig.3).

For the transmitters/receivers (T/R), according to other experiments about SL, we choose piezo transductors.

From electronic point of view, these piezos T/R are capacitor. So we have to know the value of C the capacitance.

From this, we have to create a RLC circuit that neutralizes imaginary part of impedance. We have to found the L value for our frequency.

Let Z impedance, we have $Z_{tot} = Z_R + Z_L + Z_C$, we assume that : $Z_R = R$, $Z_L = j\omega L$, $Z_C = \frac{1}{j\omega C}$ with $j^2 = -1$.

So we need here : $\omega L - \frac{1}{\omega C} = 0$ and immediatly with $\omega = 2\pi f$ we can deduce that :

$$L = \frac{1}{4C\pi^2 f^2} \quad (6)$$

This is the L value associated to f resonance frequency.

Piezos

About piezos, first we used basic undergraduate piezos but they aren't able to support a high voltage (HV) necessary for this experiment.

So, we need strong piezos. For caracterisctics, and according to other SL experiments, we need thicker piezos (≈ 1 cm).

Also, we need to favor normal modes of vibrations (piezos are disc, basically), not radial vibration modes, so we'll choose solid discs, not holed disc.

Here, we ask different laboratories and instituts for a loan of special piezos, but none of them could lend it to us. But, we found piezos from an old experiment for an other student project ($\varnothing$: 15 mm, e : 6 mm by measurement), they worked !

Water

As mentioned previously, the influence of gases in mixture is very important. Thus, to success SL, we have to degas mixture (water here). Also to avoid too much of bubble in the water.

To this, the best method about us consists of to boil the water, pour it into a flask, close it hermetically with a little part of air, and let it cool down at room temperature.

When the temperature get down, the air volume decreases and creates an under pressure, so the air trap on mixture do up to air, until thermodynamic equilibrium.

Caution and montage

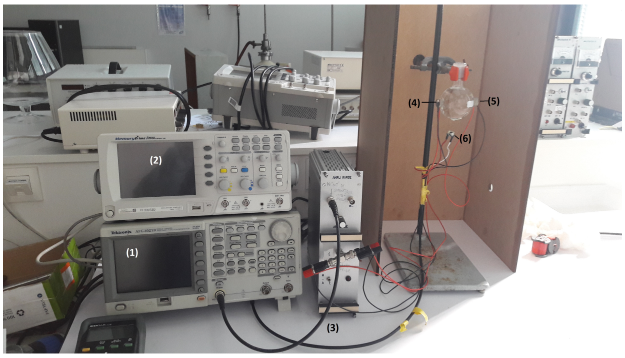
During the welding of piezos, we have to take care about temperature. Indeed, there is a temperature called CURIE point where material lose their permanent magnetic property. For this reason, we worked < 250 °C.

At last, when we'll stick paste piezos over the flask, we'll take care to eliminate every air bubble into the glue (for the wave propagation).

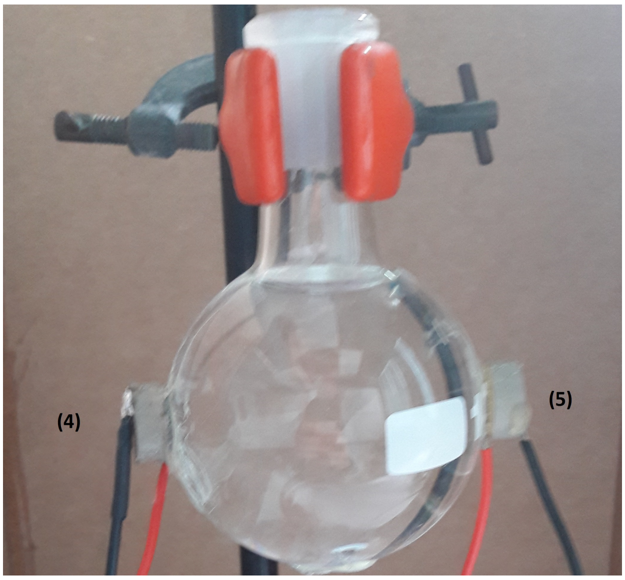
We also add a protection cage around the montage because of the HV.

Obviously, we need classical apparatus for measurements like thermometer, oscilloscope, some cables etc. (Fig.3)

And to stabilize the mixture temperature, we'll use a fan to renew the air around montage. After testing, is more efficient: before, water heated up to ≈ 30 °C (too hot) but now, temperature is around 21 °C



(a)



(b)

FIG. 3: Pictures of montages - *(1):Frequency generator; (2):Oscilloscope; (3):Amplifier; (4) and (5):Transmitters piezos; (6): Receiver piezo*

Results

Capacitance measurement

For the capacitance measurement, we use a classical multimeter. We measure here $C = 1.95 \pm 0.01$ nF. We immediately deduce L from Eq.6; $L = 24 \pm 0.04$ mH.

For obvious reasons, we prefer to take already made loop of 24 mH rather than making them.

Resonance

For the resonance, we use the piezo microphone connected to the oscilloscope and with the frequency generator we sweep a frequency range between 20 and 105 kHz.

With the oscilloscope, we measure and save the amplitudes associated to these frequencies and plot them on Fig.4.

We can show (cf. our wiki for more), that we find theoretical frequency with a Q factor around 200 need to SL.

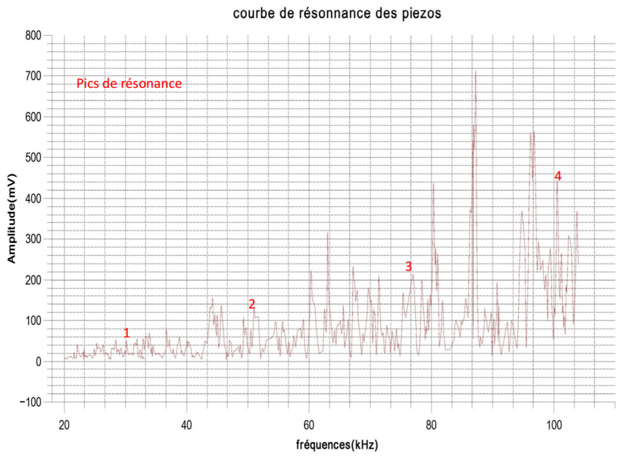


FIG. 4: Plot of resonance curve between 20 and 105 kHz - *(in kHz) 1: 25.29; 2: 51; 3: 77 and 4:100.5*

Bubble general trapping

Now we have a resonance frequency, we start begin to test bubble trapping. The only parameters that we can measure is the voltage received by piezo output and its evolution when we increase gain.

By inserting bubbles thanks to syringe, we can see if bubbles are trapped or no. When the pressure is sufficiently strong in node or anti-node, bubbles tend to migrate towards them and merge.

If pressure is too strong, bubble(s) implodes and disappears. If it's too weak, they are not affected and go up to liquid surface.

After different tests, we can resume our observations on the next figure (Fig.5). It's not a measurement but a graph to have an idea

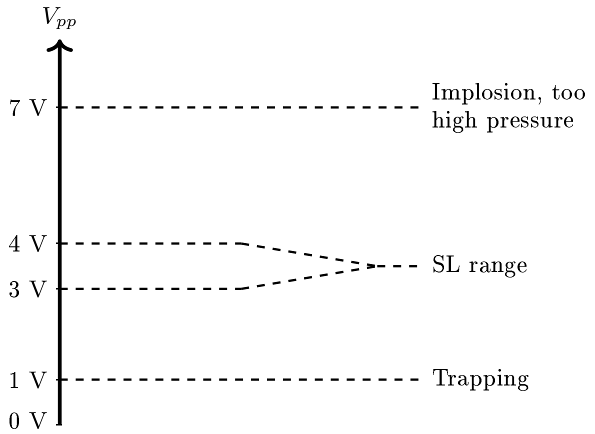


FIG. 5: Bubble behavior for different voltages from receiver piezo

Sonoluminescence

Now, we must know if we have (or not) SL phenomenon.

In view of our conditions, the light emitted by bubble(s) is weak. So, to finally observe it we must place ourselves in a room as dark as possible.

Also, in view of our eyes and SL width, we'll prefer to take picture of phenomenon with a high quality camera, in long exposure to let a lot of light and so have more chances to see SL.

The most convincing pic that to take is the next one Fig.6 taken at the last day of experiment for the fourth mode of resonance.

FIG. 6: Maybe a picture of sonoluminescence phenomenon

We can't certainly say that this is SL, because we can't push our experiment (width measurement, spectroscopy etc.), but this is our best pic.

We see the bluish/purplish light emitted and width and position seem to match with previous trapping experiment.

Exploitation

Even if we don't take any direct measure on the bubble that we produced, we've found a perfect film of SL here *http://acoustics-research.physics.ucla.edu/sonoluminescence/*.

With a MATLAB (http://fablab.sorbonne-universites.fr/wiki/doku.php?id=wiki:projet:sonolum:bulle) code that we have developed by ourselves, we can track the bubble's radius time evolution. We report it in Fig.7.

We see the same shape as for theoretical curves in Fig.1 with main big oscillations and little oscillations following each one.

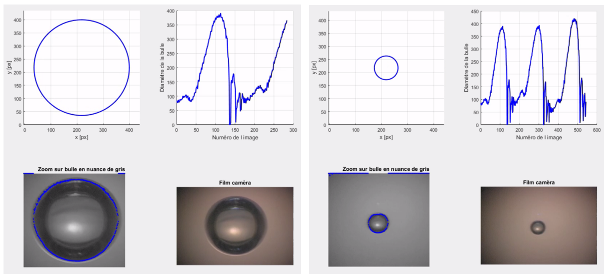


FIG. 7: Two capture of MATLAB algorithm output on two different times (interting positions)

Conclusion

We succeed here to create a SL protocol with a simple montage and apparatus and certainly succeed to get and observe SL.

We hope that we could improve the montage one day and study SL. Especially, we would try to have a radius measure of our bubble (requiring slow motion capture).

We can say that our experiment looks as a sandbox, but with more substantial, means such as best piezos, especially ordered for that we can have best results. Here we couldn't buy it because of the delivery time.

Moreover, we need a best amplifier with numerical values and with best control.

About apparatus, maybe we need hydrophone microphone to have a precise cartography of pressure field. A variable loop, a best degassing protocol with good cooling system.

Finally, we have to try to have SL on basic mode with best conditions of gas and temperature and must have **SB**SL at basic mode (in center of the flask) with more voltage.

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