Single-Bubble Sonoluminescence

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Abstract

Single bubble sonoluminescence (SBSL) is the process of creating flashes of light using ultrasonic sound waves. It is a phenomenon of considerable current interest due to the extremely high temperatures reached (above 10,000 K) and the mysteries still shrouding the details of the mechanism.

SBSL is brought about by injecting a gas bubble into a flask of liquid, typically degassed water, that is vibrating at its fundamental resonance of $\sim$26 kHz. Two piezoelectric transducers (PZTs) on opposite sides of the flask create the necessary intense standing wave. The bubble is attracted to the vibrational node at the center of the flask, where it repeatedly expands and contracts due to the changing sound pressure in the surrounding liquid. The rapid collapse of the bubble causes it to emit photons which appear to peak in the ultra-violet.

Achieving SBSL requires $\sim$1000 peak volts AC across the PZTs. This high voltage can be attained with the use of a series LRC tuned circuit in which the PZT acts as an electrical capacitor. Most of our efforts in this project were concentrated on constructing and tuning this circuit and developing a suitable amplifier to drive it. While we were also able to repeatedly capture bubbles in the intense sound field, we did not attempt to observe the SBSL light in the limited time available for this.

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1 Introduction

Although the two phenomena are generally regarded as distinct, sound waves in specific scenarios can induce light waves. The interaction is called *sonoluminescence* (SL). It was discovered in the 1930's by two German physicists as a result of research being done for World War II [1]. Ultrasonic waves were being transmitted through water in order to study acoustic radar systems. Mysterious flashing lights were seen coming from bubbles created by the sound waves. After some study, conclusions as to why the light was being emitted under these extreme conditions were made. Eventually, though, interest died out. It wasn't until the late 1980's that curiosity was rekindled due to D. Felipe Gaitian who managed to trap a single bubble [1]. This allowed the chaotic environment under which SL was usually viewed to be tamed by controllable mechanisms. It was Dr. Seth Putterman who really perfected this single bubble sonoluminescence (SBSL) set-up, encouraging much growth in the field. Now SL is not only an area of study with increasing attention, but the process of setting up SBSL or even multiple bubble SL is attainable by any lay person with a few hundred dollars and a careful eye for detail.

I will begin by going through the theory of SBSL: the effect that is witnessed when all the right factors are present as well as the current theories regarding what is occurring inside the bubble. Secondly, I will discuss the set-up of the experiment: understanding and finding the acoustic resonance and creating an LRC circuit resonant at the same frequency to produce the necessary high voltage for the PZT ultrasonic drivers. My procedure and observations, including the preparation of the water, trying to trap a bubble, and what to look for will be described next. Finally, I will conclude with where the project currently stands and some suggestions for future work.

2 The Theory

The transmission of strong, ultrasonic sound waves through a flask of liquid, water being the most basic of the usable fluids, produces a standing acoustic wave of increasing and decreasing pressure. A bubble can be trapped at the center of the flask where the antinode exists [2, 3]. In order to get the maximum amplitude of the sound wave the specific frequency of the flask's physical resonance should be applied to the flask. Generally experimentalists use either spherical or rectangular shaped containers. For example, a 100 ml spherical flask is often used. The fundamental resonance frequency in this case, (with the water filled up to the neck of the flask), is somewhere around 25 kHz.

Figure 1 shows the acoustic wave modeled as a standing wave in its fundamental mode. The reason this is the best mode to use is that this mode will experience the highest and lowest possible acoustic pressure at just one place, the center of the flask, where the bubble will reside. The circular objects on either side of the container are the piezoelectric transducer (PZT) *drivers* that generate the ultrasonic vibrations that cause the sound waves. PZTs are simply pieces of a special ceramic that expand and contract when voltage is applied across them, or *vice versa.* When a voltage oscillating at the correct frequency and amplitude is applied to

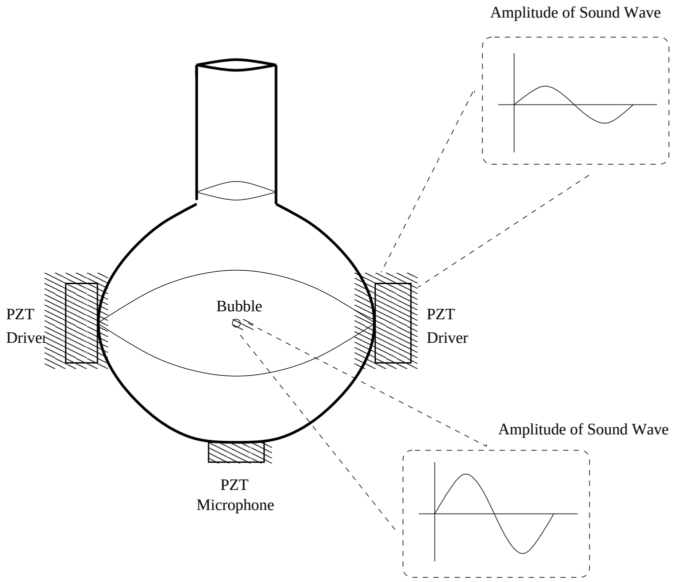

Figure 1: Typical spherical flask with PZT drivers placed symmetrically on either side and the PZT microphone on the bottom. At resonance the sound wave will act as a standing wave in its fundamental mode, producing the most intense sound wave at the center of the flask.

the drivers an inserted bubble will be attracted to the center of the flask. Since the necessary voltage is rather high, around 1000 volts, a electrically resonant LRC circuit is used to boost the much lower voltage obtained from a signal generator and small audio amplifier. As shown in Figure 1, a third smaller PZT at the bottom of the flask acts as a microphone to record the response of the water and flask to the vibrations of the drivers.

If conditions are right, the bubble will stay suspended and the sound waves will cause the bubble to jiggle wildly. The bubble will start out at around 5 microns in diameter. As the low pressure part of the sound wave travels through the bubble it will expand to nearly 10 times its size [4]. Acoustical pressure around the bubble is at a minimum when the bubble's size is at its maximum. Additionally, the molecules have separated far enough apart during this expansion to cause a partial vacuum inside the bubble [5]. Therefore, as the pressure increases from zero to around 1.3 atm the bubble will suddenly collapse. Refer to Figure 2 taken from Dr. Putterman's article in *Scientific American* in February of 1995 to see the bubble's dimensions, the sound pressure, and time scale of the collapse. The rapid implosion stops when the repulsive forces of the atoms inside the bubble equal the water pressure pushing in [5]. At this point, (the bubble being around 0.5 microns), it bounces back to about a 1 micron size, then smaller again, oscillating at the applied acoustic frequency of ∼25,000 times/sec. [4]. Each time the bubble decreases in size it emits light that appears to peak in the ultra violet. Part of the ambiguity about SBSL is that researchers can't see all the wavelengths of light that are emitted by the bubble because shorter wavelengths are not transmitted through water. The light they do see, however, indicates a temperature of at least 10,000 K to 50,000 K. As researchers from

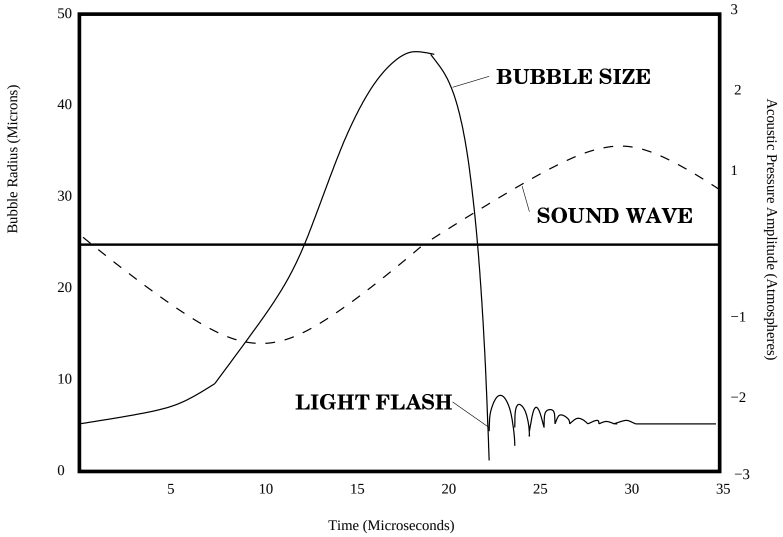

Figure 2: The bubble's radius increases as the sound wave pressure decreases. The bubble size is maximum (50 microns) when the pressure is zero. Once the sound wave increases in pressure (1.3 atm) the bubble rapidly collapses, emitting light at each sucessive contraction [3].

Lawrence Livermore National Lab and the Naval Postgraduate School of Monterey state:

> At the instant of SL emission, the bubble is so small (diameter about 1 micron), it is collapsing so rapidly (wall velocity about Mach 1), and the pressure ($P \gg 1$ atm) and the effective temperature ($T \gg$ 10,000 K) are changing so quickly that standard theories or experimental techniques have not been able to illuminate how these conditions combine to produce very brief SL flashes [6].

What is known is that the high temperatures cause the ionization of the gas inside the bubble. With the electrons free to roam around, there is a cool, dense plasma of atomic nuclei left in the bubble [4]. When the bubble is collapsing the electrons recombine into molecules, de-exciting, and thus release photons. Further explanation can be found through the shock wave theory. This is primarily put out by Putterman and is presently the accepted view. The bubble has been measured to implode at a speed faster than the speed of sound, some even faster than Mach 4 [7]. Regardless, the bubble contracts fast enough to cause a spherical shock wave to implode with increasing amplitude and speed. The temperatures get so extreme because the temperature behind the shock wave is higher than that in front of it. Thus, once the shock wave hits the center it explodes outward, passing through the bubble a second time [3].

3 The Equipment

I followed the standard set-up and used a 100 ml Pyrex spherical flask. Two PZT drivers obtained from the sonoluminescence kit sold by Channel Industries[1] had previously been epoxied to the sides of the flask at symmetric points, as shown in Figure 1. These are ring shaped, with inner diameter 8 mm, outer diameter 20 mm, and thickness 4.5 mm. The two driver PZT's are wired in parallel, so the total driver capacitance is twice that of either PZT alone. A smaller and much thinner PZT taken out of a Radio Shack microphone had also been previously glued to the bottom of the flask for the pickup. Standard 50Ω coaxial cables were used to connect the drivers and microphone to the other parts of the circuit.

The signal running through this circuit was provided by a Hewlett Packard 50 MHz function generator, model 8116A. While this gave a stable output, unfortunately the minimum frequency step size at 25 kHz is rather large – 100 Hz – compared to the recommended step size of 10 Hz or better. To get around this problem a 'fine tuner' was made by applying a continuously variable control voltage of 0–9 volts obtained from a 9 volt battery to the FM control input of the function generator. Since the display of the function generator didn't change as the frequency was varied in this way, the exact frequency was read on a separate frequency meter. With this system it was possible to vary the frequency in amounts as small as 1 Hz.

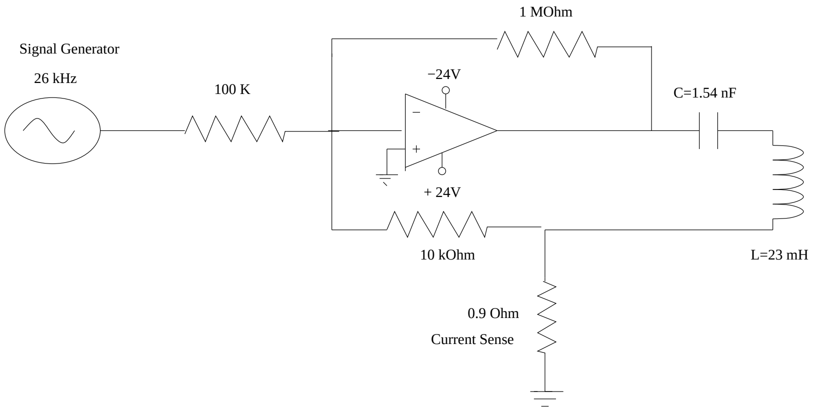

Figure 3: The signal generator was connected to the operational amplifier which then went to the inductor (coil) and capacitor (the PZTs). The four resistors are arranged to make the opamp into a constant-current source, whose output current should be proportional to the input voltage from the signal generator.

Even with the boost provided by the LC resonant circuit the output voltage of the function generator isn't high enough, so some type of audio amplifier is needed. I started with a huge old vacuum tube amplifier and moved on to a much smaller car radio booster amp from Radio Shack, but first one and then another of these units failed. The last amplifier I used – which worked very well – was a Model 440C 50-watt operational power amplifier from OpAmp Labs (`www.opamplabs.com`) . It was wired up with some resistors to act as a constant current amplier,

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[1] Channel Industries, Santa Barbara, Ca, webrefhttp://sonatech.com/index.htm. The sonoluminescence kit of two drivers and one microphone PZT is still available for $95.

as shown in Figure 3. The opamp was powered by two 24 volt power supplies, since these were readily available, but it could be run at up to ±40 volts if necessary.

As explained in the following section, the elements of the LC resonant circuit were the PZTs (C) and a homemade coil (L). The inductance of the coil was varied over about a 10% range by moving a piece of ferrite material in or out of the center of the coil. The ferrite material was actually a telephone line noise filter purchased from Radio Shack.

4 Making the LC Resonant Circuit

There are a few different aspects to trying to obtain SBSL. I began by measuring the resonant frequency of the flask, since this is also the frequency at which the LC circuit has to resonate. I then measured the capacitance of the PZTs by resonating them with a known inductor. This allowed me to calculate the inductance needed for the coil and to go ahead and construct it. Finally, as described in section 5, I prepared the water by degassing it and played with the completed set-up to trap bubbles and perhaps see the flashing light of SL.

4.1 Finding Acoustical Resonance

I knew that the frequency of the fundamental mode should be somewhere around 25 kHz for this size and type flask. I found the exact value by hooking up a signal generator to an amplifier and then to the PZT drivers. By observing the microphone signal on the oscilloscope I could see the intensity of the flask's vibration displayed as a sinusoidal output. Sweeping the frequency near 25 kHz I found that my flask resonated around 27.1 kHz, as shown in Figure 4. It can be seen that the perfect peak one would expect to see from the theoretical idea behind resonance doesn't always come out so smoothly in reality.

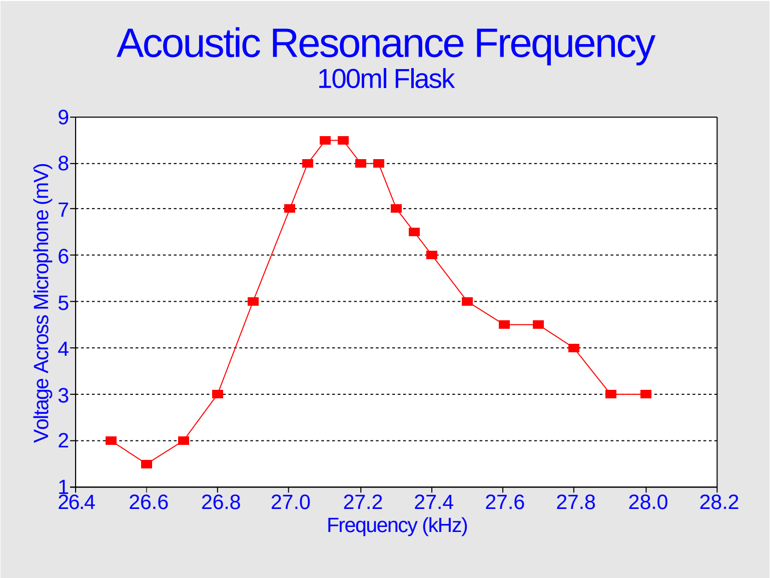

Figure 4: An acoustical resonance curve for the 100 ml flask.

4.2 Understanding Resonance of an LRC Circuit

Let me start by explaining what is going on between the inductor and capacitor that allows high voltages to be created very efficiently, with only a little power.

Resonance in a series LRC circuit occurs when the impedance of the circuit is at the lowest possible point, allowing the highest possible current to run through the circuit. The impedance Z of a resistor is the same as its resistance R. The resistance remains constant because it is not affected by frequency, as is apparent by Ohms Law: $R = V/I$. Impedance for an inductor L and a capacitor C, however, is called the reactance X and *is* dependent on frequency. Ohm's Law for both is as follows:

$$V_c = IX_c \text{ and } \mathrm{V_L} = \mathrm{IX_L}$$

Where X_c is the reactance of the capacitor and X_L is the reactance of the inductor:

$$X_c = \frac{1}{\omega C} \text{ and } \mathrm{X_L} = \omega \mathrm{L}$$

X_c equals the current divided by the angular frequency ω and the capacitance. X_L equals the current times the angular frequency and the inductance. This causes the capacitor's reactance to be inversely dependent on frequency, as displayed by Figure 5. The inductive reactance, on the other hand, is directly related to frequency, as shown in Figure 6.

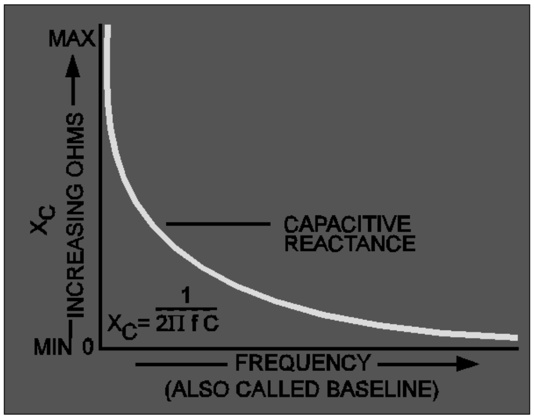

Figure 5: Capacitive Reactance [8].

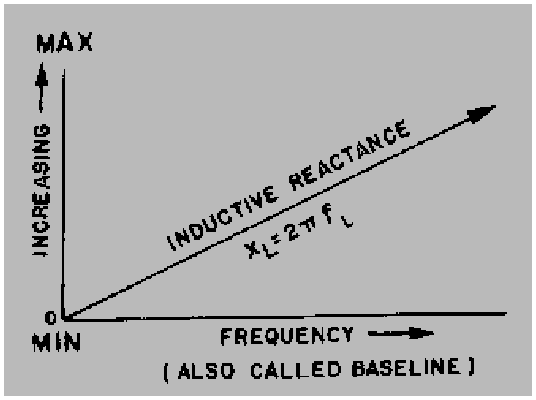

Figure 6: Inductive reactance [8].

Where the two curves overlap is where one will find the resonant frequency of the LRC circuit, as shown in Figure 7.

At resonance the voltages across the inductor and capacitor are 180° out of phase. The total impedance can be modeled as the vector sum of the net reactance and the resistance. Since resistance is constant, it is a vector with a set magnitude on the x-axis of the graph in Figure 8. The reactance of the inductor and capacitor, on the other hand, add in the y-axis. The total reactance and the resistance then add to give one resultant vector. The magnitude of this is the total impedance of the circuit Z. One can see from the figure that when the reactance of the

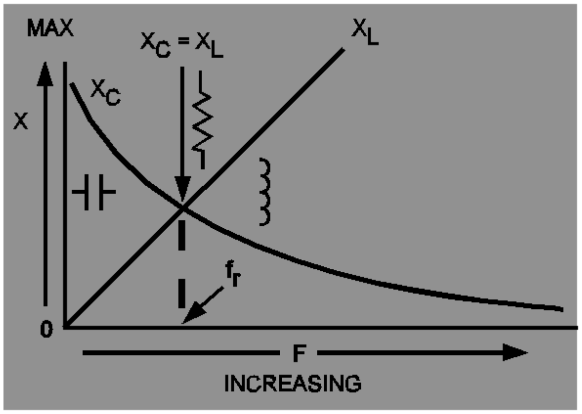

Figure 7: The resonance condition [8]

inductor and capacitor cancel out by being of equal magnitude (having the same amplitude), but opposite value (180° out of phase), they cancel out, giving the lowest possible impedance, the smallest Z. This is the desired state one wants his/her LRC circuit to be in, in order to allow the highest amount of current to flow through the circuit and into those PZTs. It must be noted, however, that this scenario is an ideal case. In reality there is some additional resistance inherent within each component that prevents the circuit from being as efficient as it could be at this theoretical resonance.

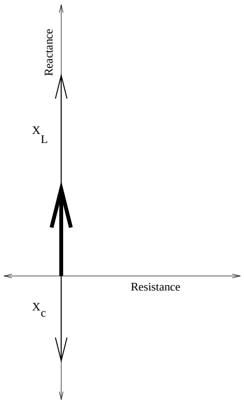

Figure 8: The inductive reactance and the capacitive reactance add to form one resultant vector in the y-axis.

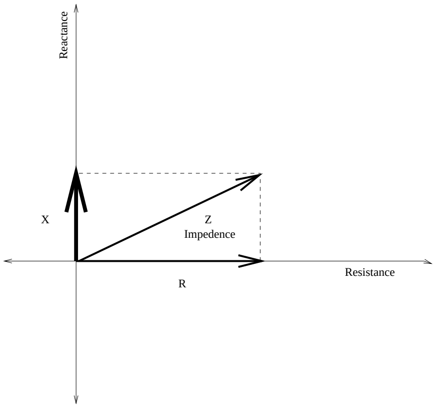

Figure 9: The resultant vector of the reactance is added to the resistance to create the impedence.

I needed to match the resonance of this circuit to that of the flask for two reasons. Primarily, one needs the ultrasonic sound waves to be strong enough to trap a bubble. The acoustical waves need to be around 110 decibels to get SL [3]. Though this volume is quite high, perhaps deafening, a 25 kHz frequency is not in the range of human hearing. By perusing through other people's experiments, I knew a voltage of around 1000 volts peak-to-peak V_{pp} running across the PZTs would be needed. Besides physically pushing a high voltage through the PZTs, which wouldn't be very efficient or safe as the power output would be up around 250 Watts, the other way to obtain a strong acoustic wave is by setting the electronic resonance of the circuit to that of the physical resonance of the flask. Secondly, because one signal generator is driving this whole circuit a crucial part of this project is to get the circuit to resonate electrically at the same frequency as the flask. When that occurs everything is in tune and SBSL is possible.

4.3 Finding Capacitance

As mentioned previously, I needed to measure the capacitance of the PZTs in order to estimate the inductance of the coil I would need to make to achieve resonance at the fundamental frequency of the flask, 27 kHz.

To measure the capacitance of the drivers I began by creating an LRC circuit with a precisely known 100.0 mH ±0.1% standard inductor. By varying the frequency in many small steps I traced out the resonance curve shown in Figure 10, which has a maximum at 40.35 kHz. Later on I repeated this measurement with another standard inductor of exactly 10.0 mH, for which the resonance frequency was found to be 12.89 kHz.

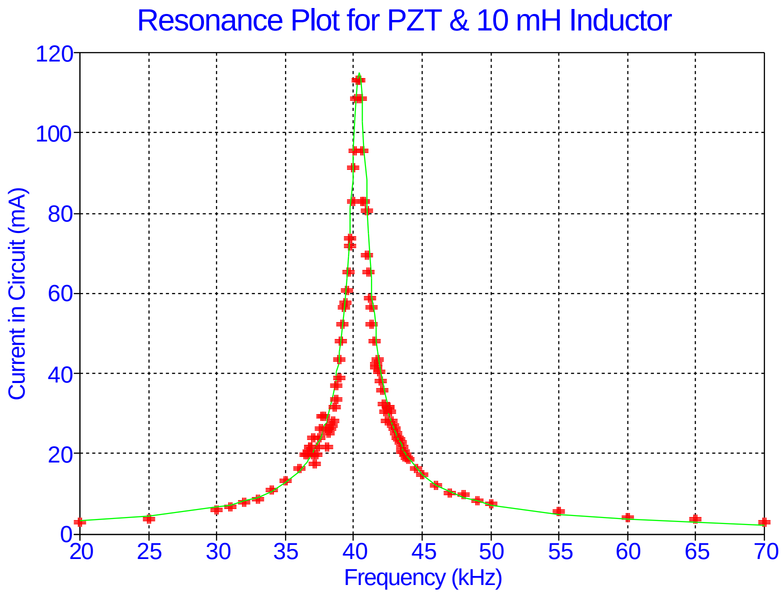

Figure 10: Plot of current vs. frequency to show the resonance frequency of the LRC circuit at 40.35 kHz.

At the resonance the voltage across the capacitor is equal to the voltage across the inductor, so that one has the following equations:

$$V_L = V_c \implies I\omega L = \frac{I}{\omega C}$$

$$C = \frac{1}{\omega^2 L} \implies \omega = \frac{1}{\sqrt{LC}}$$

Knowing the measured resonant frequencies and the inductances I could then substitute these values and obtain the capacitance of the PZTs, as follows:

$$C = \frac{1}{[2\pi \cdot (12.89 \text{ kHz})]^2 (0.100 \text{ H})} = 1.52 \text{ nF}$$

or

$$C = \frac{1}{[2\pi \cdot (40.35 \text{ kHz})]^2 (0.010 \text{ H})} = 1.56 \text{ nF}.$$

To double check these measurements I decided to calculate the PZT capacitance directly from the dimensions, using the equation for a parallel plate capacitor with area A and plate separation d:

$$C = 8.85 K_\epsilon \frac{A}{d} \text{ (pF/m)}$$

Here K_ϵ is the relative dielectric constant of the PZTs, and C is expressed in units of picofarads over meters. Using the PZT dimensions given in section 3, and taking into account that the central hole in the PZT reduces its area, one finds that

$$C = 2 * 0.519 * K_\epsilon \text{ pF}$$

for the capacitance of the two PZTs in parallel.

There is some uncertainty about K_ϵ; a graph on the Channel Industries web site indicated $K_\epsilon \simeq 1250$ for their type 5400 ceramics, while another source of information suggested that $K_\epsilon \simeq 1700$. These two estimates for K_ϵ predict a total PZT capacitance of 1.30 nF or 1.77 nF, respectively, in approximate agreement with the value 1.54 nF measured directly.

4.4 Making My Own Inductor

If one changes the core of an inductor, (or, incidentally, the distance between two adjacent inductors), one can change the inductance, and thus the frequency at which the circuit resonates. For instance, when I placed a ferrite rod inside the inductor I was causing the magnetic field to concentrate, which increased the inductance L. Because the resonant frequency ω equals $1/\sqrt{LC}$ the ferrite rod brought it down. If I could build an inductor that would cause the circuit to resonate about 1000 Hz higher than the resonance frequency of the flask, I could bring ω down enough by inserting a ferrite rod through its center.

I began construction of my own inductor by calculating the inductance needed to resonate with the capacitance of the PZT drivers, measured as described above, as follows:

$$L = \frac{1}{C\omega^2} = \frac{1}{(1.54 \text{ nF} * (2 * \pi * 27 \text{ kHz})^2)} = 23 \text{ mH}$$

Next, I cheated a bit by going online to Shavano Music Online[2] where one can enter the inductance one needs and a program at the site will compute a list of coil dimensions for various possible wire gauges. This gave me a rough estimate of what my inductor's dimensions needed to be. I proceeded to wind approximately 500 feet of 22 gauge solid hookup wire from Radio Shack around an empty plastic wire spool with a length and diameter of about 2 inches. It is important to note that this size wire was believed to be thick enough to handle the current that would be running through it. The real test as to whether I had wound enough wire came by inserting the coil in the circuit and adjusting the number of times the wire wrapped around itself according to the resonance frequency of the circuit. Once I got the desired resonance, peaking around 27.5 kHz, I stopped winding the coil. This completed the circuit I needed to obtain SBSL.

5 Procedure and Observations

In order for the way in which I proceeded through my experiment to make sense it is important to understand the environment I was working in. Upon undertaking this project, I was an undergraduate physics student going into my senior year. I was allowed two months in an optics laboratory to work on an experiment of my choice, my choice being SL. The object was not to complete things to any said point, as another student could pick up the project wherever I left off. I was encouraged, instead, to focus on learning about and developing the experimental apparatus for SL. While this approach was rewarding, it did leave me with relatively little time for trying out the completed apparatus.

The process of actually trying to obtain SBSL involved a few standard steps. I always began by cleaning out the flask and preparing the water. Next, I measured the resonance frequency of the flask and tuned my circuit to that frequency. Lastly, I adjusted the applied voltage and fine-tuned any other necessary components until I obtained the desired outcome.

5.1 Preparing the Water

Many different liquids, as well as gasses for the bubble, can be used to obtain SL. Playing with those substances is one area of high activity in SL, the simplest of which, water and air, though, work just fine. To begin with, the water must be very clean. I used de-ionized (DI), filtered water obtained from the electroplating lab. Secondly and most importantly, the water must be degassed. There is a very small range between too much gas and not enough that has to be found through experimentation. After filling a separate clean 250 ml flask about half full with the filtered DI water, I degassed it using a liquid-nitrogen-cooled sorption pump. I kept the vacuum on until just before the water stopped bubbling completely. The other way of getting the same effect is by simply boiling the water, which takes about 15 minutes[1]. I then poured the degassed water into my thoroughly cleaned 100 ml flask until it barely reached the neck of the flask. The object was to try to obtain spherical symmetry with the water.

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[2] `http://www.colomar.com/Shavano/construction.html`

5.2 Trying to get SBSL

Once the water was degassed the steps I went through were as follows:

- I began by finding the exact resonance frequency of this particular flask of water, which is sensitive to many incidental variables like the exact level of the water, the temperature of the water, etc. This could be done with the signal generator hooked up directly to the driver PZTs, without any inductor, or even without the amplifier. The results varied between about 26.5 and 27.2 kHz.
- Inserting the coil back into the circuit, I had the oscilloscope displaying the microphone output as well as the current sense. I placed the ferrite rod in the coil and played with it until the current peaked at the same frequency that the flask response peaked at. Sometimes a high-pitched squeal could be heard coming from the flask while doing this.
- Using a syringe I gently injected bubbles into the flask. Catching a bubble was never an issue because as long as the driving voltage was high enough a bubble would inevitably be caught. The trick was for how long and would it do what I wanted it to do? As I increased the driving amplitude from the signal generator the bubble would jiggle more and more and then get very stable. If I kept increasing it the bubble would shoot off to the side. This is called the *extinction threshold* and denotes the point where the sound is too loud. The driving voltage just below the extinction threshold is where one will find a bubble that lights up. At this point I paid close attention to the sine wave being put out by the microphone. If a bubble exists in the flask it will show up as tiny ripples within the larger sine wave. One can't always see the bubble with the naked eye, though back lighting can help with this, but one *can* always 'see it' displayed on the oscilloscope.
- If one wants to actually see the distant flash of blue-ish light that is emitted, one must have complete darkness in the lab. This can be tricky, as one needs to be able to adjust the function generator and oscilloscope. At this point one simply needs time and high amounts of concentration. If all is in order, then one should see a faint light emanating from the center of one's flask as one ups the driving amplitude.

6 Conclusion and Outlook

SBSL was a great experiment to work on for the summer. I learned a tremendous amount about circuits, resonance, and sound waves. My time was spent primarily in setting up the equipment to obtain SBSL and understanding the physics behind it. For this reason, seeing light from the bubble was never actually achieved. On the other hand, I was able to trap many bubbles, and the desired effects were seen when I played with the driving amplitude.

The outlook to this project involves future students taking over the set-up to continue trying to achieve SBSL. After this, many possible variations on the basic experiment can be explored, for instance, the liquid medium can be changed, the gas content inside the bubble can be changed, the light flashes from the bubble can be measured with a photomultiplier, etc. Clearly there are many fascinating areas of research that can be picked up from where this project left off.

Acknowledgements

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