Developing a Reproducible Sonoluminescence Procedure

J. Shields[1, a)] and E. Sánchez[1, b)]
Department of Physics, Portland State University, P.O. Box 751, Portland, OR 97207-0751, USA

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Sonoluminescence (SL) is an attractive field of study when minimal space, funding, and equipment are available. Most of the materials required to create the basic effect are readily available to any university or college lab. SL is particularly exciting, because the mechanism through which light is produced remains unexplained. However, there are many conceivable configurations to create SL, and many parameters to control, sometimes with little feedback. This paper outlines some of the difficulties with creating a SL setup, in order to aid further study.

I. INTRODUCTION

To create sonoluminescence, a gas bubble in a fluid must first be trapped in a standing sound wave. Bubbles below a certain size (section I A) move towards the anti-nodes and become trapped. At the anti-node, the bubble is rapidly expanded and compressed by the changing pressure field. Given the right conditions, the bubble will bounce off of its internal gasses as they are compressed. During this bounce, a very short burst of light is emitted. The source of this light is still unknown, and there are multiple competing theories as to how it is generated.

A. Theory

Trapping objects at anti-nodes may seem counterintuitive at first. Typically, acoustic levitation traps objects at nodes. Similarly, a Chladni plate traps dust at nodes, not anti-nodes. The key is that bubbles are compressible. Consider a small bubble sitting between a node and an anti-node in a standing wave (figure 1). During the high pressure phase, the bubble is small and experiences a buoyancy force towards the node, following the negative gradient of the pressure field. During the low pressure phase, the bubble is larger and therefore experiences a larger buoyancy force towards the anti-node, following the negative gradient of the pressure field. Thus, averaged over a cycle, the bubble experiences a force towards the anti-node[1]. Such forces involving small particles subjected to acoustic fields are generally known as Bjerknes forces, or *primary* Bjerknes forces.

This is only true for bubbles which are smaller than the resonant radius. Bubbles above this critical radius are attracted towards the nodes[2,3]. This radius can be shown to be

$$a = \frac{1}{2\pi f}\sqrt{\frac{3\gamma^* p_0}{\rho_0}}, \qquad (1)$$

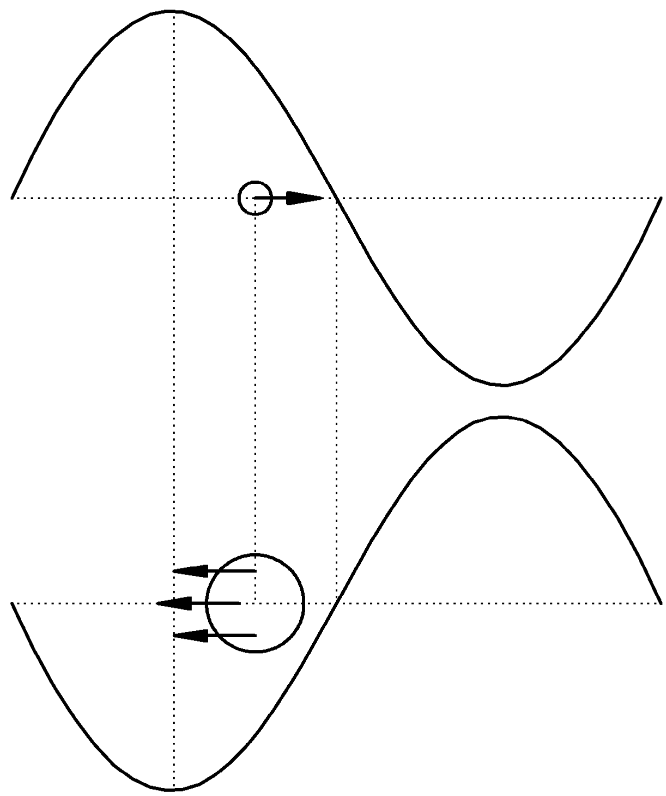

FIG. 1. A conceptual diagram of a bubble in a standing wave, between a node and an anti-node. Circles represent bubbles. Arrows represent force. Sinusoids represent pressure.

where a is the resonant radius, f is the frequency of the applied sound field, γ^* is the ratio of the specific heats of the gas in the bubble (C_P/C_V), p_0 is the ambient pressure in the liquid, and ρ_0 is the ambient density of the liquid[4]. For air bubbles in water at room temperature and pressure, this equation is approximated as

$$fa \approx 3\,\mathrm{m/s} \qquad (2)$$

The bubbles also create their own acoustic field as they oscillate. Bubbles smaller than the resonant radius attract each other, as do bubbles larger than the resonant radius. However, a bubble smaller than the resonant radius will repel one that is larger than the resonant radius,

[a)] Physics Department, Portland State University.; Electronic mail: shields6@pdx.edu
[b)] Electronic mail: esanchez@pdx.edu.

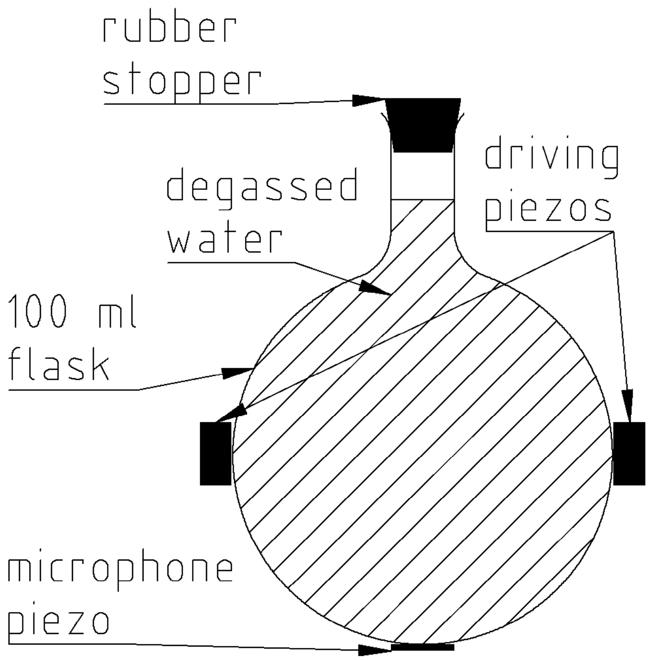

FIG. 2. A schematic of the resonating chamber used. Cross hatching indicates water.

and vice versa[5]. This is referred to as a *secondary* Bjerknes force.

B. Apparatus

1. The Flask

A 100 mL flask was used for the resonating chamber (figure 2). Annular piezoelectric transducers were fixed to the sides of the flask facing each other, using epoxy. A piezoelectric disk was fixed to the bottom of the flask to serve as a microphone.

It is, of course, important to solder the leads of the transducers on before mounting them to the flask, since one side will be inaccessible once the epoxy is applied. Enamelled magnet wire (around 24 AWG) works well for the transducer leads. It is recommended that the flask and leads be attached to some rigid structure, since repeated repositioning will eventually break off the leads. This should be done at the top of the neck of the flask, so as not to interfere with its resonance. If the leads do break off, heat should only be applied sparingly when soldering them back on. Piezoelectric transducers will be damaged by excessive heat. This is one advantage to using thin wires; they conduct less heat away from the joint being soldered, thereby reducing the necessary heat to be applied to the joint. It is important that none of the wires touch. Some of them will be at hundreds of volts during operation and could short out.

During the sonoluminescence procedure, the flask is filled with degassed water (section II A). When not in use, the flask should be closed with a rubber stopper. This can preserve the degassed state of the water for a few days, depending on how much air has been injected into the water and how many bubbles were left in the flask before storing it (section II D).

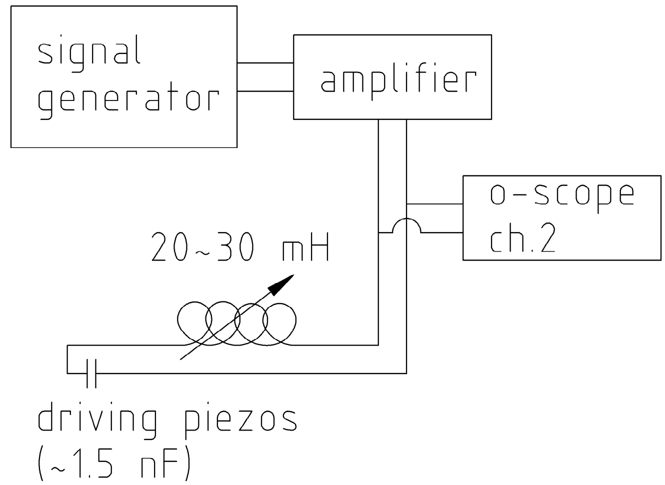

FIG. 3. A schematic of the circuit used to drive the piezoelectric transducers.

A 100 mL flask occupies a convenient zone for sonoluminescence. With a diameter of about 6.1 cm, a standing acoustic wave can be set up in the flask at around 25 kHz when filled with room temperature water. This frequency is above the audible range for humans, but not excessively high. Recall from equations 1 and 2 that higher frequencies trap smaller bubbles at the anti-nodes. This also has the great advantage of using standard, mass-produced lab equipment.

2. The Circuit

The circuit used to drive the transducers is shown in figure 3. A signal generator provides a sine wave to an amplifier, which then passes the amplified signal to an RLC circuit. No resistor is shown in the diagram, since one does not need to be deliberately added to the circuit. The inductor will likely have an internal resistance of around 20 Ω. The capacitor shown in the circuit diagram represents the transducers. Electrically, they behave much like a capacitor, completing the RLC circuit.

It is recommended that BNC connections and coaxial cables be used for the majority of the circuit. This will reduce noise, and make assembly and disassembly easier. Depending on the amplifier used, it may be necessary to fabricate connections to make the amplifier compatible with BNC connections. During operation, an oscilloscope should be used to monitor the output of the amplifier. This can be accomplished with a T connector.

To connect to the transducers, a BNC connector should be incorporated into the rigid structure holding the flask

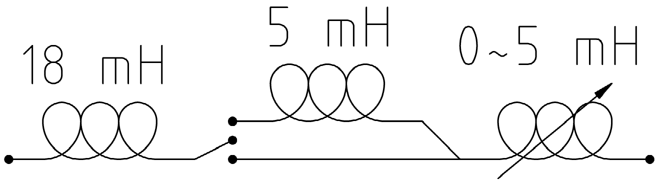

FIG. 4. A schematic of the design used for the variable inductor.

(section I B 1). This way, when the setup is disassembled, the transducers can easily be disconnected from the circuit without moving the leads to the transducers. Similarly, a BNC connector should be connected to the leads of the microphone.

To connect the inductor, it is recommended that it be incorporated into a coaxial cable terminating in BNC connectors. This can be done by cutting open the outer jacket conductor of a coaxial cable and soldering the inductor in series with the then exposed leads. Thus, connecting the cable in-line with a given load adds the inductor in series with the load and ground. The inductor should be firmly secured to the cable after soldering, so it does not become disconnected during handling. This is easily accomplished with electrical tape. It could also be incorporated into the rigid structure holding the flask. However, one may need to make repeated modifications to the inductor before it covers an appropriate range of inductances. Such modifications are much easier to make when the inductor can be easily removed from the setup.

3. The Inductor

The inductor must cover a range of inductances, such that the circuit's resonance can be tuned from about 24 to 31 kHz. For the 1.5 nF capacitance which came from the transducers, this corresponds to a range of about 29 to 17 mH. It must also be able to withstand large voltages, since the resonant side of the circuit will be at hundreds of volts.

Such an inductor is not easily found off-the-shelf, and must be constructed. This can be done by winding one from scratch, but it is much easier to piece together (see figure 4) from commercial inductors. Inductors can be wired in series to get to the lower limit of the necessary range. Then, a variable inductor can be added in series to cover a continuous range. If a suitable variable inductor cannot be found, one may be able to dislodge the ferrite rod from an inductor, which may then be slid in and out to change its inductance. If the variable inductor does not cover the whole range, a switch may be used to add inductors on the fly, extending the range of possible inductances. This essentially provides a coarse and fine control to the variable inductor. During operation, a strong electromotive force is induced in the ferrite rod. Touching the rod with bare hands appreciably changes the resonance of the circuit and can sometimes result in an unpleasant spark. As such, some tape should be wrapped around the end of the rod, so it can be manipulated without altering the resonance of the circuit or shocking the operator.

II. PROCEDURE

A. Degassing

To begin using the apparatus, degassed water must first be prepared. This can be done either by boiling the water or using a vacuum pump, though the vacuum pump is more effective. To degas it through boiling, distilled water is boiled for 15 minutes with a loose lid over the container. Since the transducers can be damaged by heat, this should not be done in the flask. To degas it with a vacuum pump, fill the flask with enough distilled water to fill the neck about half way. Then, either attach a cheap mechanical pump or a vapor trap and mechanical pump. If no vapor trap is attached, the mechanical pump may be damaged by the water vapor. The pump is then turned on and left running until the water stops outgassing. For the pump used, this took about 10 minutes. An effective way to connect the mechanical pump to the flask is by running a piece of high pressure tubing through a rubber stopper. After degassing, the neck of the flask should be about a quarter full. If too much water has left the flask, it must be refilled to a higher level than before and degassed again.

After the water has been degassed, it should be aerated with argon. This can be done by inserting a tube into the flask and passing argon through the tube so that it gently bubbles through the water. It is important to use a low flow rate of argon for this. Otherwise, water may be ejected out the neck of the flask. The flow of argon should be turned on before inserting the tube into the flask, so that this will be apparent before any water is actually ejected. It is recommended that the flow of argon be controlled with a regulator. The aeration should proceed for 1 to 10 minutes. It has not yet been determined how much aeration is actually necessary.

Once the water has been degassed and aerated with argon, a rubber stopper is firmly placed in the neck of the flask to prevent air from dissolving into the water. The water is then left to sit for at least 3 hours before any bubble trapping is attempted.

B. Circuit Assembly

With BNC connections on all of the components, setting up the circuit is relatively easy. The output of the signal generator should be connected to the input of the amplifier. The output of the amplifier, one side of the inductor, and the input of channel 2 on the oscilloscope should all be connected with a T connector. The remaining side of the inductor should be connected to the driving transducers. Finally, the microphone should be connected to channel 1 on the oscilloscope.

To begin, the amplifier is turned to its minimum setting, the oscilloscope is turned on, the inductor is set to its minimum setting, and the signal generator is turned on. A sinusoidal pattern of about 0.1 V and 20 kHz is a reasonable setting to start at for the signal generator. The gain on the amplifier is then increased until a few volts are read on channel 2 of the oscilloscope. This is a convenient channel to trigger off of, since it isn't dependent on anything but the output of the signal generator and the gain on the amplifier.

At this point the leads of the transducers may be at a few hundred volts, and they definitely will be after the setup is tuned. Touching them with bare hands is unpleasant and should be avoided.

C. Finding Resonances

The rubber stopper is then removed from the flask. Using a clean eyedropper or syringe, water is withdrawn from the flask until the meniscus is 1 to 2 mm above where the continuation of the flask's spherical surface would be. After adjusting the oscilloscope so that the microphone signal is clearly visible, the frequency of the signal generator is then slowly increased. The amplitude of the microphone output will rise and fall as this is done, and the frequencies at which it is a local maximum are recorded. One of these will be the resonant frequency of the circuit, but the rest will be the resonances of the flask. Some of the higher resonances may be quite small. If this is the case, the inductor is then set to a different value and the sweep repeated.

Inputting noise to the circuit and performing a Fast Fourier Transform does not reveal the resonances and is not worth the effort. The method of sweeping the input frequency is much easier and more reliable.

D. Trapping Bubbles

It was found that 29.8 kHz was an effective frequency for trapping bubbles, so the signal generator should be tuned to a resonance near this frequency. Then, the inductor is tuned to maximize the amplitude of the microphone signal. This should increase its amplitude by a factor of 2 to 5.

At this point, a clean eyedropper or syringe is used to release droplets of water into the flask. This water should either be drawn out of the flask, or come from the water that was withdrawn earlier (section II C), such that the meniscus stays at the level specified in section II C. The purpose of this is to introduce small air bubbles into the water. Using equation 2, one sees that the resonant radius should be around 0.1 mm. Fortunately, the flask magnifies the bubbles somewhat. However, it is still recommended that a black backdrop be placed behind the flask and a small light, such as a portable reading lamp, be placed under the flask. This makes observing the bubbles much easier. It is not necessary to forcefully inject the bubbles into the water. Thanks to the secondary Bjerknes force between bubbles, small bubbles will condense together until they are larger than the resonant radius, at which point they will begin repelling the smaller bubbles and moving away from the anti-nodes.

If they bubbles are not being trapped, the input frequency and inductance are tweaked until trapping occurs. It may also be necessary to change the signal amplitude to the RLC section of the circuit, either higher or lower. This requires patience from the operator. Counterintuitively, increasing the amplitude does not always result in stronger trapping. At very high amplitudes, bubbles smaller than the resonant radius will begin to be repelled from the anti-nodes as well[6]. When attempting to trap bubbles, the operator should look for signs that the Bjerknes forces are becoming appreciable. These include: bubble-to-bubble attraction, bubble-to-bubble repulsion, erratic bubble motion, or any bubble motion other than simply floating directly up. The sound emitted by trapped bubbles also noticeably distorts the microphone output from a regular sinusoid. At very high amplitudes, oscillations can be excited below the input frequency, down into the audible range. If this occurs, the input amplitude is too high.

When introducing bubbles into the flask, large bubbles will aggregate, and then crash into the walls of the flask and adhere to them. Eventually, the top half of the flask will be covered in bubbles. This alters and damps the acoustic resonance. To remove them, a rubber stopper should be placed firmly in the neck of the flask and the connections to the driving transducers and microphone should be removed. The flask is then gently rotated around, so that the very large air bubble created by the neck of the flask absorbs the bubbles stuck to the surface of the flask. The connections should then be reattached and the stopper removed.

E. Creating Sonoluminescence

Once a bubble is trapped, attempting sonoluminescence can begin. A high sensitivity camera is trained on the flask. Hamamatsu's C2400 series of cameras is suitable for this purpose. Single bubble sonoluminescence only occurs under very specific conditions. Utilizing a high sensitivity camera allows the operator to recognize when they have grazed this set of parameters and then hone in on them.

With a bubble trapped at the center of the flask, the operator places a dark shroud around the camera and flask, and darkens the room. If the camera can be damaged by bright light, the operator should be made aware of this, and take care not to turn it on in a lit room. Once the room is dark, the operator turns on the camera. This transition should be done quickly. Otherwise, the bubble may dissolve before the camera is turned on. The operator then closely monitors its output while gently varying the input frequency and inductance. When any light is seen at the approximate location of the bubble, the operator stops varying these parameters together, and then varies them one at a time to maximize the light output.

III. RESULTS

Although sonoluminescence was not observed with this particular setup, it is believed that only slight modifications are required to achieve it, since this is a relatively common design.

Creating an inductor in the proper range and learning to trap bubbles can be time intensive. If possible, one should try to observe and learn from someone who is already familiar with these tasks, to try and expedite the process.

A. Additional Observations

In addition to motions explicable through the secondary Bjerknes forces mentioned earlier (section I A), more elaborate bubble behavior was observed. Bubbles would often appear to orbit around apparently nothing. The period of these orbits was far too slow to be attributed to a retarded secondary Bjerknes force, which might explain these self orbits. On rare occasions, the frequency of these orbits was as low as a few Hertz, with the bubble traversing the whole flask. However, it was usually on the order of tens of Hertz, with an orbital diameter of a few millimeters. Larger orbits were less common, and corresponded to lower frequencies.

A more common phenomena was chaotic motion of the bubbles. The bubbles would quickly dart around in unpredictable, almost Brownian trajectories. This seemed to be more common with large bubbles. Previous research[7] asserts that the chaotic nature of bubbles in acoustic fields is attributable to the after-bounces of the bubble lasting well into the next acoustic cycle, giving the bubble memory. However, this only addresses the chaotic nature of the bubble's radius, not the position of the bubble in space.

B. Future Analysis

Further refinement of the technique for trapping bubbles is needed. It is not enough to simply wander around in frequency and inductance, since doing so results in a considerable amount of time being spent on trapping bubbles. A clear and consistent method is needed for honing in on the optimal trapping parameters. A method for quantifying how well the bubbles are being trapped would be useful, since it would enable the use of numerical optimization methods.

While the method of bubble absorption mentioned in section II D is effective, it can be time consuming. A faster method for cleaning the bubbles off of the inside of the flask may help with this.

With the driving transducers placed opposite of each other on the flask, strong anti-nodes are created at the center of the flask and at the walls near the transducers. Often, bubbles would be attracted towards the wall anti-nodes, and crash into the wall. It may be helpful to use an odd number of symmetrically placed transducers. Thus, the strongest anti-node would be at the center of the flask, while the wall anti-nodes would not receive any constructive interference, at least not from any primary (non-reflected) sound.

It may also be helpful to place the transducers on a plane that is not perpendicular to the axis of the flask. The main force with which the primary Bjerknes force must contend is the ambient buoyancy force. With the transducers arranged perpendicular to the axis of the flask, and thereby perpendicular to gravity, they are fighting the buoyant force in their weakest direction. In a skewed setup, they would not be fighting the buoyant force in their weakest direction, so a lower amplitude might be needed to trap the bubbles. Tilting the flask might also work, but it would distort the meniscus of the water, which might interfere with trapping.

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