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by W.A. Steer PhD

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About...

Sonoluminescence

Sonoluminescence is a little-understood phenomenon whereby light is emitted by tiny bubbles suspended in a liquid subjected to intense acoustic fields. The aim of this work was to construct apparatus to enable the observation of single-bubble sonoluminescence, to investigate its basic properties, and leave a kit and instructions to form the basis of a future final-year undergraduate experiment. It was found that despite the apparent simplicity of the setup, to obtain successful and repeatable sonoluminescence required great care in the selection and tuning of system components, and a good degree of patience. The precision and stability of the signal generator was found to be particularly critical, and (if not building your own as I did) a modern digital piece of instrumentation is highly recommended. The widely-reported increase in bubble brightness at low temperatures was readily confirmed, and a simple Mie scattering arrangement configured to monitor the bubble size gave results consistent with those already published.

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Introduction

Sonoluminescence was first observed in an ultrasonic water bath in 1934 by H. Frenzel and H. Schultes at the University of Cologne, an indirect result of wartime research in marine acoustic radar. This early work involved very strong ultrasonic fields and yielded clouds of unpredictable and non-synchronous flashing bubbles, now termed "multi-bubble sonoluminescence". Such a chaotic phenomenon did not lend itself to detailed scientific investigation. Study of sonoluminescence then made little progress until 1988, when D. Felipe Gaitan succeeded in trapping a stable sonoluminescing bubble at the centre of a flask energised at its acoustic resonance - single-bubble sonoluminescence (SBSL). However their interest soon waned, and the research was subsequently taken up by Dr S. Putterman et. al., at UCLA, California.

Putterman pursued SBSL, published numerous papers, and established many of the characteristics which are now taken for granted. Once per acoustic cycle, coincident with a sharp decrease in bubble size, bluey-white light is emitted in a brief flash shorter than 100picoseconds in duration, with incredible regularity. Despite the results that have been obtained, the actual mechanism by which sound is converted to light remains elusive, not least because of the difficulty in measuring the conditions inside a pulsating bubble whose diameter is measured in micro-meters. It is generally agreed that the adiabatic compression of the bubble leads to very high interior temperatures, but beyond that, shocks, plasmas, ionisation and photo-recombination, Bremsstrahlung radiation, and even fusion are all hotly-debated possible explanations.

In Scientific American, February 1995, Putterman published an introductory overview paper on sonoluminescence together with a practical guide in the "Amateur Scientist" section of the same issue. By making the subject accessible to a wider audience, interest escalated dramatically, and given the apparent ease with which sonoluminescence could be obtained, many university groups attempted it. A revised and more detailed version of their "Amateur Scientist" guide can be found on the World Wide Web at http://www.physics.ucla.edu/~hiller/sl/, and is maintained by Robert Hiller, a student of Putterman.

Within the Physics Department here at UCL, sonoluminescence was offered last year (1996-97) as a final-year undergraduate project. Unfortunately the quest for the glowing bubble proved fruitless for those involved... a story which has been echoed by several other groups around the world. So, I was "commissioned" by the department to get the experiment up and running over the summer, ready for next year.

I too used the Scientific American article as my primary guide, but successfully "saw the light" within a couple of weeks. I found the article to be quite correct as far as it goes but that, probably due to the constraint of brevity, it fails to emphasise some significant details as much as might be desired. Combined with the somewhat optimistic impression of the ease with which sonoluminescence can be obtained, this may explain others' failed attempts and subsequent discouragement. I attribute my success to extensive experience in hands-on practical work and electronics, and ready access to a variety of electronic bits and pieces from home!

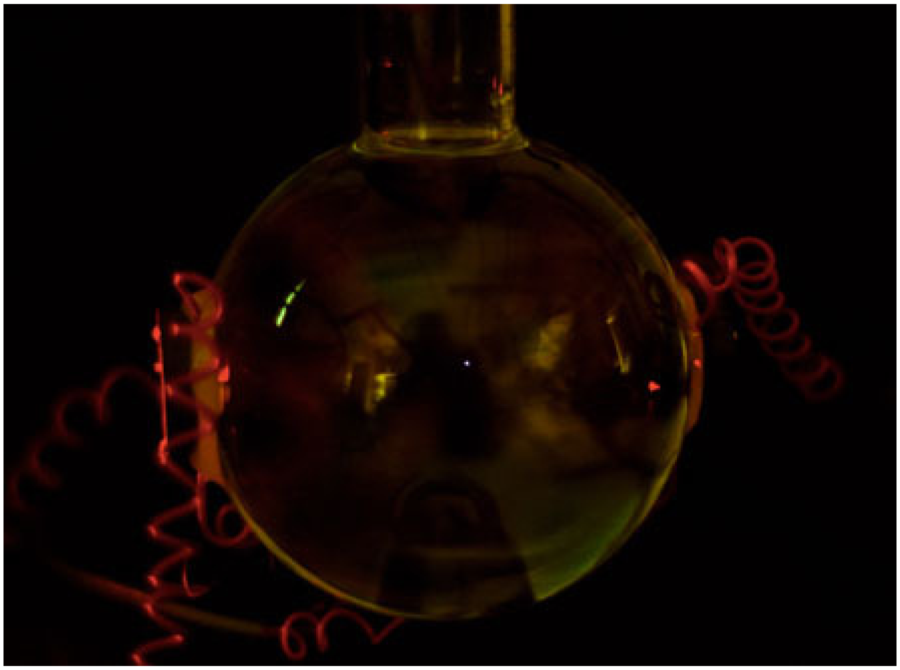


Photo 1: Success... that elusive glow! (small bluey-white dot at centre of flask)

Detailed Method

Preparation of a flask for use as a sonoluminescence vessel

We scoured glassware catalogues for suitably narrow-necked 100ml round-bottomed flasks. Finally we chose a distillation flask [Griffin and George part FHD-230-030G], which happened to be ordinary soda-glass. As supplied, its very long neck had an extra tube protruding from the side; we truncated the neck just below this to leave about 7cm of parallel-side neck.

The flask was thoroughly washed, using hot water and Fairy Liquid (the original, not Lemon variety), and rinsed. The final rinse was with cold distilled water.

Three piezoelectric transducers, as described by Hiller, were supplied to us by Channel Industries Inc. The two larger transducers, 20mm diameter by 4.4mm thick (and with an 8mm diameter hole through the centre) were used as the drivers, and the smaller transducer, 6mm diameter by 2mm thick, was used as a microphone.

Lightweight hook-up wire (7/0.2mm) was cut into ~10cm lengths to make the leads for the driver transducers, and the ends stripped of insulation and "tinned" with solder. To reduce mechanical stresses on the connections the leads were coiled, by winding them around the inside tube of a biro. Three very small (approx. 2mm dia., 0.5mm high) dabs of solder were then applied to each silvered surface of the transducer, just inside the outer circumference. The exposed part of one end of each lead was cut down to a mere 2mm, and then held over a solder dab on the transducer and gently pushed down with a soldering iron for a second or so, to make the connection. Soldering was carried out quickly as the silvering on such transducers is liable to be destroyed if too much heat is used. It was also discovered that a mild electric shock can be received from the transducer during thermal expansion/contraction following soldering!

Transducers are polarised - applying a DC voltage one way round causes the ceramic to expand, while opposite polarity results in contraction. To ensure all transducers in an application can be wired in phase, they are supplied with one side marked with a red cross. By convention I wired the red sides of the transducers (with red wires) to the signal, and the reverse (with black leads) to the ground. The solder connections described were small enough that they didn't touch the surface of the flask when the transducer was held against it. Photo 2 illustrates the connection to the transducers.

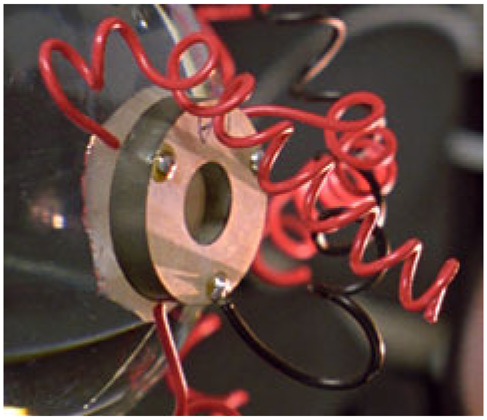


Photo 2: Wired and mounted transducer

For the small microphone transducer, the lightest grade screened audio cable was used (about 2mm outside dia.). About 4cm of outer sleeving was stripped off, and the inner covered wire and screen separately coiled. The end of the inner wire was prepared as above, and soldered to the red side of the transducer using just one tiny solder dab. The screen was soldered to the reverse.

These more rugged connections (compared to Hiller's design) didn't have any adverse effects on the acoustics.

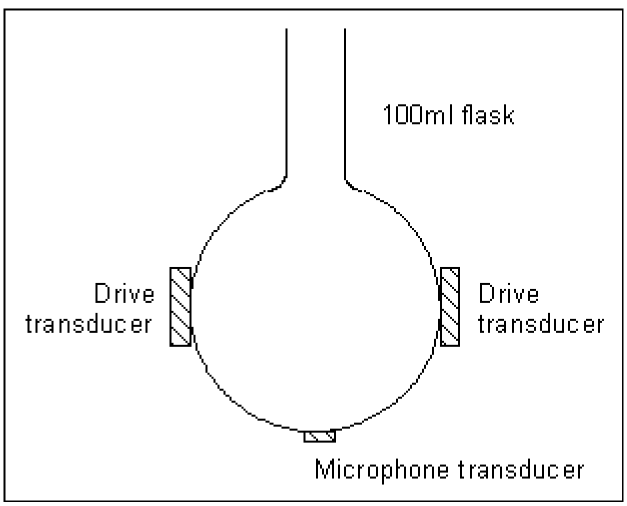


Figure 1: Flask, showing location of transducers

Judged by eye, target positions for the transducers were marked on the flask using an OHP pen. The small transducer was to go at the very bottom of the flask, and the two larger ones diametrically opposite each other on a horizontal axis through the centre of the flask -- see figure 1.

Araldite Rapid was mixed, and a sufficient coating applied to the first transducer site on the flask. Using a three-finger clamp, the flask was then gripped with that site facing downwards. The transducer was placed on a paper towel on the side of a individual-portion breakfast-cereal packet (a "springy" support!) and working swiftly, Araldite was applied to its face. Finally the flask was lowered on to the transducer and left for 20minutes to set.

For safety reasons, the **red** sides of the transducers, later to be connected to the several hundred volt drive signal, were glued **towards** the glass where they cannot be touched.

Once the first transducer had stuck, fresh Araldite was mixed and the procedure repeated for the next driver transducer, then again for the microphone.

Electrical circuit

Stable trapping of an air bubble at the centre of a flask requires an acoustic standing wave in the water, so the flask must be excited at its natural resonance. When filled with water, a 100ml round-bottomed flask resonates at approximately 25kHz.

Piezo-ceramic transducers are the standard "loudspeaker" devices for ultrasonics but, unlike hi-fi speakers, they require several hundred volts to drive them and draw very little current. Because the piezo transducers behave electrically like capacitors, a suitable inductor can be wired in series with them to form a tuned circuit, which "matches" them to the loudspeaker-output of an audio amplifier -- see figure 2. The inductor trades current for voltage, and while presenting a low impedance to the amplifier (output swing around $40V_{p\text{-}p}$), generates the necessary 700V or so across the transducers.

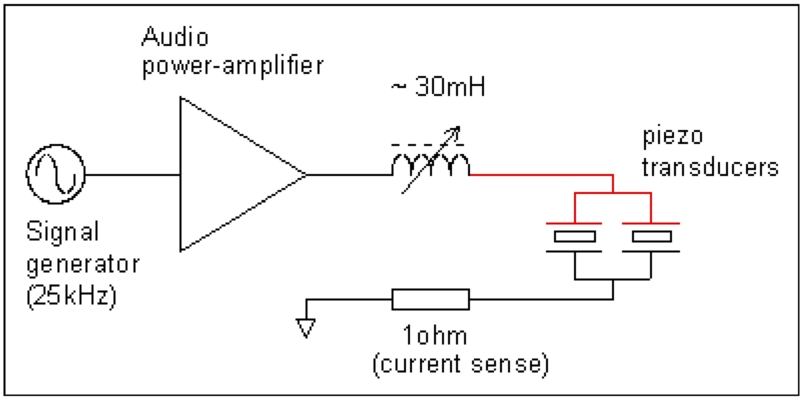


Figure 2: Piezo transducer drive circuit. The section shown in red operates at high voltage.

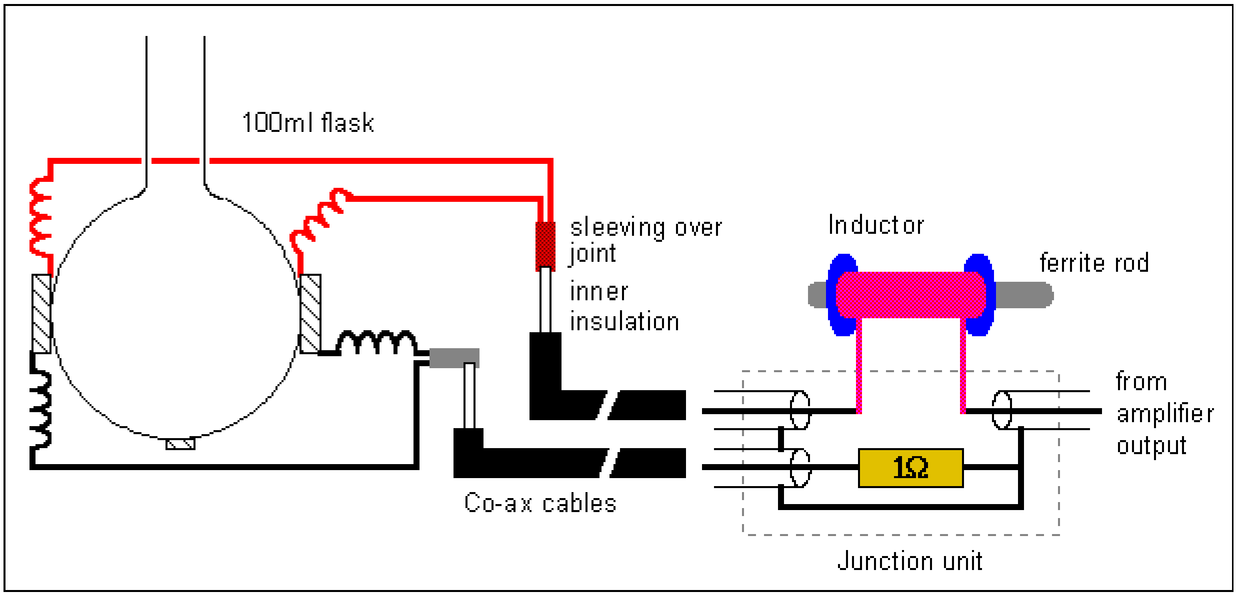


Figure 3: Physical wiring diagram.

The two drive transducers were wired in parallel by soldering the two red wires together, and the two black wires together. Those junctions were each soldered to the core of separate 1metre lengths of standard 50ohm coaxial cable, and the joint covered with sleeving for safety. In each case, the *screening* of the 50ohm cable was cut away where it emerged from the outer covering. Both the 50ohm cables, and the microphone cable, were firmly clamped to the retort stand using cable ties, to prevent tension on the connections to the transducers. BNC plugs were fitted to the other ends of the two cables, and plugged into to a junction unit linking in the 1ohm resistor and the inductor -- see figure 3. The core of the cable to black wires connects to the 1ohm resistor (current-sense), and the core of the coaxial cable to red wire to the inductor.

By keeping all the cable screens at ground potential in this way, a BNC lead from a scope could be inserted at any point in the circuit using a T-piece without causing short-circuits. The use of screened cables is essential to minimise radiation of 25kHz, which might otherwise interfere with the low level signals involved in measurements.

Given the capacitance of the transducers and the frequency at which we operate, an inductance of around 30mH is required to form a resonant circuit. The inductor needs to be made of thick enough wire to take the required current, but not so thick that it becomes physically huge, which might also lead to a fall in performance. Our "best" inductor consisted of a partially-filled 500g plastic spool of 0.5mm diameter (24swg) enamelled copper wire, tuned by sliding a ferrite rod (usually sold as MW/LW radio aerial) up and down the centre of the spool. It was found that to prevent power loss to eddy currents, owing to the large fringing field, the coil had to be sited well away from any conducting object - particularly that the axis of the coil did not intercept any nearby metal.

The wiring and coil were measured to have a DC resistance of about 10ohms (bypassing the transducers of course), and present an impedance of about 100ohms to the amplifier when tuned to resonance. It is this impedance which determines the upper limit on the power that can be transferred to the transducers given a finite voltage swing from the amplifier. In practice, we found that a mere 1Watt of power needed to be transferred to the drive circuit to achieve sonoluminescence.

Signal Generator

Although Hiller implies that any lab signal generator will do, we found some to be useless, and most general purpose instruments frustrating at the least. It is vital that the amplitude of the sinewave output does not jump about as the frequency is varied, and that the frequency varies smoothly, also without jumping about. To find the resonances of the flask, it is essential that the frequency can be set to within 30Hz or better at 25kHz. Common [old-fashioned, analog]* signal generators [of the type you find in Universities]* typically sweep a decade of frequency in one revolution the knob, making such precise adjustments difficult. The generator needs to be stable, not drifting too much with time. Our first success was obtained with an off-the-shelf lab generator, but very soon I decided to build my own instrument. It sweeps about 24-27kHz in one turn of the knob, and is stable to within a few Hertz after having been on for a short while.

The frequency was measured by connecting the separate square-wave output of the signal generator to a digital frequency counter. Note: With some waveforms and signal levels, frequency counters are liable to report wildly incorrect readings. Occasional use of a scope to check the readings are reasonable is mandatory!

* If I'd used a modern digitally-synthesised signal generator such as the Fluke/Philips PM5138A (the luxuries I now get working in an Industrial R&D lab!), then I probably would have avoided a lot of problems! - December 2004

Preparation of the water

Air bubbles can only be driven to sonoluminescence in water which has substantially less than the usual amount of dissolved air. Previous researchers have reported that a partial pressure of around 150mmHg, one fifth of atmospheric pressure, is ideal. Water can be "degassed" either by boiling, or by evacuating the space above it in a sealed flask. We adopted the former method, being simpler - though less controllable.

A 100ml quickfit flask was just-over half-filled with distilled water, then heated in an electric mantle at full power, and maintained at a rolling boil for 15minutes. After switching off the heat a rubber bung was gently placed into the neck of the flask before leaving it to cool. As the water cools the bung is sucked in and leaves a vacuum above the water, preventing more gas dissolving back in. Sometimes cooling was accelerated by holding the bulb of the sealed flask under running cold water, and gently swirling its contents. With the bung kept in place, the water can remain degassed for many days if required. The procedure was repeated with a second 100ml flask, so that a quantity of over 100ml of de-gassed water was prepared.

For the experiment, the sonoluminescence flask is held in a 3-finger clamp. If the flask contained water from a previous run, then that was poured away by lifting and tilting the entire stand (not just the flask, which could lead to breakage of the wires or connections). There was a tendency for the water to gain dust, fluff, broken glass... etc., so the last of the water was always swirled out to remove any debris.

Holding the stand at about 45 degrees, the freshly-degassed, room-temperature water was poured into the sonoluminescence flask, letting it run down the side. The flask was filled to the top of the spherical part; I tried to fill so that the lowest part of the meniscus is in a position to form a continuation of the spherical shape, but a millimetre or two either side didn't seem too critical.

Tuning up

With the flask now full of water, it is necessary to tune the signal generator to the best resonance of the flask. Having settled on an acoustic resonance, the inductor is then tuned to maximise the drive to the transducers.

The microphone transducer was plugged into the oscilloscope input. As confirmation that all is well, if the scope sensitivity was turned up (and a fairly low sweep rate selected), the trace would jump if the flask was gently tapped.

The amplifier, signal generator and frequency counter were wired up and turned on. Before proceeding, the signal generator was allowed to stabilise - with my generator about 5minutes was found to be ample.

If the ferrite-rod was in the coil (inductor), it was removed at this point, before tuning up. Care was taken not to drop the rod as they are very fragile.

With the scope timebase on 10μs/div, and sensitivity on 0.1V/div., the gain control on the amplifier and/or oscillator was adjusted to get a reasonable trace on the scope. It was sometimes useful to also monitor the direct output from the amplifier on the second channel on the scope (5V/div) to ensure the waveform was not clipping (as it might if the levels are set too high).

Sweeping through the range of my signal generator (23-26.5kHz), acoustic resonances were located by watching for maximal amplitudes of the microphone signal. One was usually found near 25.5kHz and another at 25.1kHz at room temperature. It is not unusual for the waveshape from the microphone to look skewed or distorted between acoustic resonances. Confirmation that an acoustic resonance has been found is obtained by momentarily touching or gently squeezing the flask - the microphone signal level drops appreciably as the vibrations are damped.

Having located the strongest acoustic resonance, the ferrite rod was placed in the coil and slowly moved in and out to find electrical resonance, which further maximises the signal from the microphone. Because this increased the drive considerably, it was necessary to change the scope sensitivity to 1V/div.

Trapped-bubble behaviour

With experience, it became much easier to trap a bubble and make it glow. Patience was essential, particularly at the outset.

Back-lighting was used to make the tiny bubbles visible: a small torch was placed behind the flask, directed towards its centre.

With the electronics tuned up, the drive amplitude was adjusted to obtain a microphone signal somewhere between 1 and $7V_{p\text{-}p}$. With no bubble present, the trace on the scope should be a clean sine wave.

Using a narrow, clean pipette, a small amount of water was withdrawn, the pipette tip lifted above the water surface, and the contents gently dropped back into the flask. This action induces some bubbles, and with practice, a force sufficient to generate just one or two bubbles can be judged.

At the instant the bubbles are injected, the microphone signal usually decreases in amplitude and fluctuates in waveform for a few seconds, before an equilibrium is established.

The general behaviour of the bubble at different sound levels and dissolved gas content is summarised in figure 4.

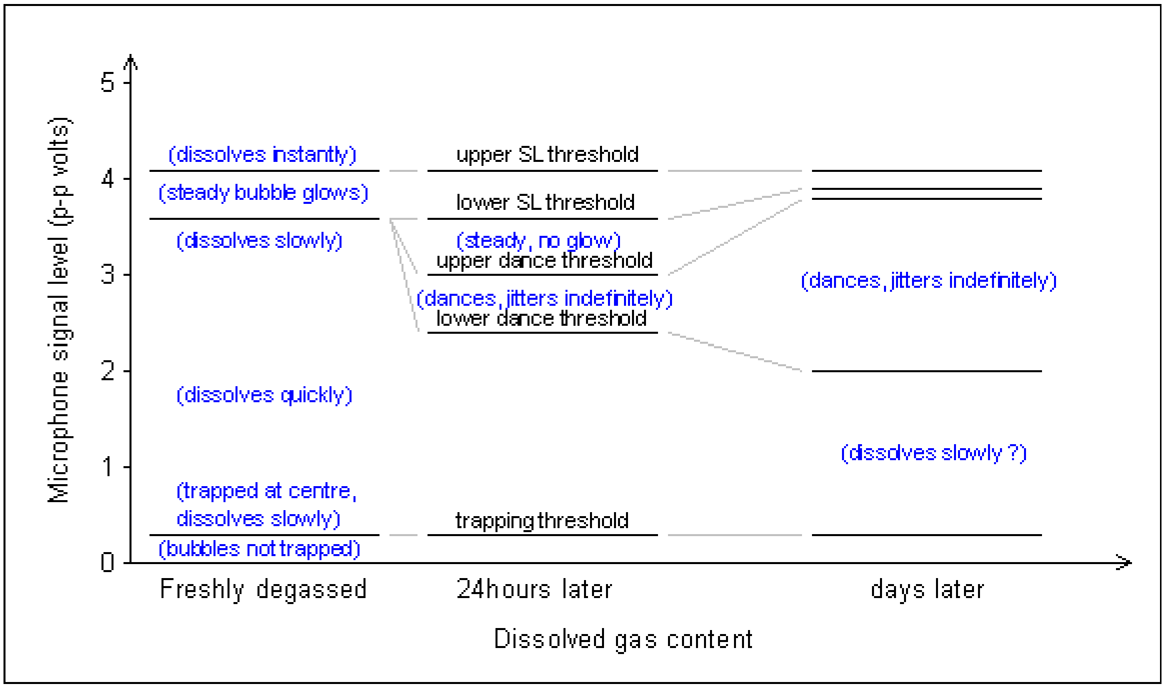


Figure 4: Dependence of bubble characteristics on sound intensity and dissolved-gas content.

Variations in the threshold levels were observed between runs, with the upper SL level lying anywhere from 3V to 7V. There are inherent practical difficulties in obtaining an accurate record of the form above - when does "a long time to dissolve" become "does not dissolve"? Repeatedly injecting bubbles will invariably lead to increase in the dissolved-gas content, perturbing the very system we are trying to measure. Despite these difficulties, the chart gives a good indication of the main characteristics, namely:

- With well degassed water, the major part of the sound range causes rapid dissolving of the bubble. Consequently sonoluminescence can only be approached by dropping in a bubble once the sound is already in the correct region, and is very stable. Indefinite trapping occurs only in the SL region, and the dancing regime is rarely observed.
- A small amount of dissolved gas enables the formation of an energy band in which the bubble is trapped indefinitely, yet dances and jitters. The upper dancing threshold is well defined, with an abrupt transition from frantic jittering to peaceful stability. At the lower end of the scale, the point of change from steady to gently oscillating bubble is rather more subjective.
- As the water ages, regaining dissolved gas, the gap between the upper-dancing and upper-SL thresholds narrows - making SL more difficult and less stable. Dissolving becomes much slower at low sound

levels.

- With very gassy water, small bubbles may form in the vicinity of the trapped bubble, and feed it, sometimes to the point of instability (bubble dissolves/rises to surface). A cycle may be set up where more small bubbles coalesce, making a new bubble, which expands... Additional bubbles can form on the side of the flask, upsetting the symmetry of the sound field - the central bubble then jitters wildly over a large range of sound levels and cannot be controlled to produce sonoluminescence. The jittering gets progressively worse, and the bubble flits all around the flask as the water gains more and more dissolved gas.

If the sound level was high, say anywhere above the upper dancing threshold, then injected bubbles were found to "stream" very rapidly to the flask centre. Above the upper SL threshold they just disappeared at the centre, while below the threshold a bubble remained after the streaming. At lower sound levels the bubbles take a more leisurely drift to the centre. Whenever the trapped bubble was lost, or could not be seeded, the sound level was adjusted, and another bubble injected.

A typical description of bubble-behaviour in intermediately degassed water would run as follows:

> "A level of 1 to 1.5 volts p-p on the microphone was sufficient to trap the bubble at the centre of the flask. At around 2.7 volts the bubble began to dance about the centre, spanning a distance of a couple of millimetres. With more power still, the bubble became slightly larger and "fuzzy". At $4V_{p\text{-}p}$ the jittering started to subside, and between 4.1V and 4.5V the bubble was very small, and stable. At the uppermost end of this range, the bubble visibly glowed if the room was dark. At about 4.5V the bubble suddenly disappeared altogether."

Viewing the glowing bubble

With a small *stable* bubble, trapped by a sound level just below the upper threshold at which the bubble can exist, the room was blacked out and the backlight switched off. It was found to be helpful if there was still just enough room light to be able to make out the flask. A faint bluey-white glow, like starlight, was seen from the bubble in the centre of the flask - sonoluminescence! If the drive level was cautiously increased, the glow from the bubble could be made brighter, but too great an increase caused the bubble to re-dissolve and be lost. When lost, the drive could be backed off a fraction, and a new bubble dropped in. After stabilising for a second or so, the new bubble glowed as before.

Under all circumstances, best sonoluminescence was observed when the flask was clamped as loosely as possible in the stand.

Interpretation of the microphone signal

When the amplitude is in the "fuzzy, jittering bubble" region or higher, the microphone trace on the scope will normally have some kind of ripple superimposed -- see figure 5. Depending on the amplitude of the ripple however, it may only be apparent as a mild distortion of the underlying sinewave.

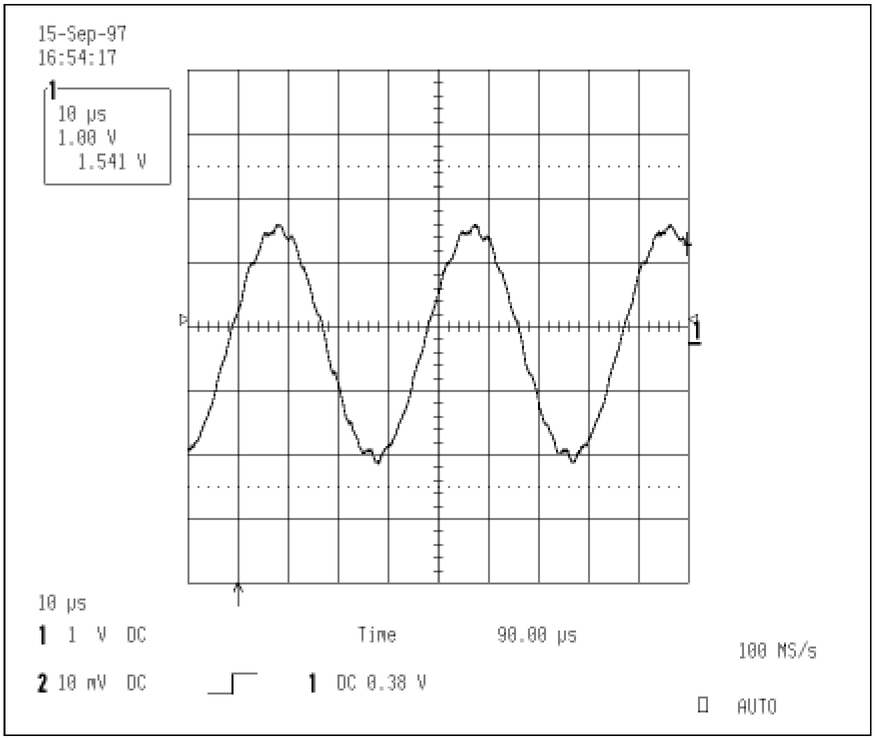


Figure 5: Ripples seen on the microphone signal when a trapped bubble is present.

The strength of the ripple depends on the exact driving frequency used, and the tightness of grip of the flask in the stand - the loosest grip gives the brightest SL bubble and largest ripple. The ripple is highly characteristic and moves along the fundamental waveform as the drive amplitude is adjusted. It moves rightwards (later in time) as the drive is increased, and when the bubble is glowing at its brightest, at the upper sonoluminescence threshold, the ripple has a peak at the centre of the crest of the main wave and also causes the trough of the wave to flatten out. The ripple appears to be a harmonic resonance of the flask, excited by the shock wave of the collapsing bubble. Hiller et al (private correspondence) have described placing a microphone in the water right next to the bubble and observing merely an instantaneous "click" at the point of collapse. When the drive is increased too far the bubble is lost and the scope trace returns to a pure sinewave -- see figure 6.

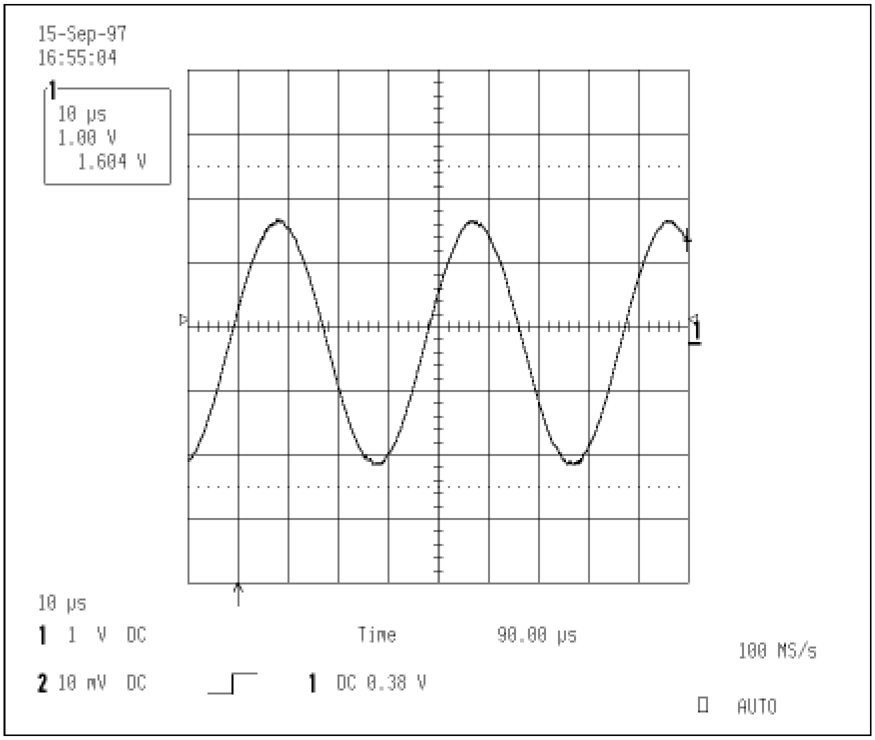


Figure 6: Ripples disappear with the bubble if the amplitude is driven too high.

If the scope trace is not steady then something is wrong, and *the bubble won't glow*. In this case, or just to increase the brightness further, fine adjustment of the drive frequency (up to 30Hz either way) may help. Maximising the amplitude of the ripples on the trace can be a useful guide.

Temperature-dependence of bubble brightness

A bucket of dry ice was positioned on its side above the flask in such a way as to allow the cold gas and cooled air to flow around it. This method enabled the flask to be cooled down to nearly freezing by a non-contact means, thus not changing the acoustics. It was observed that the frequency of the acoustic resonances in the flask decrease with temperature, being about 300Hz lower near freezing point.

In our particular flask, the 25.5kHz resonance was best at room temperature while below about 16C the 25.1kHz resonance became far better. [The temperature of the water was measured by inserting a digital thermometer probe into the water - but it was found that the probe gave bizarre readings while the sound was on.]

Qualitatively, it was observed that the bubble got much brighter when the water was cooled. Subjectively it also appeared (when back-lit) that the bubble was larger than at room temperature, though this was not confirmed.

Summary of findings and typical figures

Water: distilled, boiled for 15minutes then sealed and left to cool under own vacuum.

Transducer drive: of the order of $700V_{p-p}$ swing required.

Inductor specification: around 30mH. Partially-used 500g spool of 0.5mm diameter enamelled copper wire, tuned by sliding a ferrite rod up and down the centre of the plastic spool.

Microphone output: typically between 3 and $7V_{p-p}$ for sonoluminescence. [Better guide than drive levels]

Frequency generator *minimum spec.*: tuneable to within 30Hz at 25kHz. Stable to within 30Hz over ten minutes or more. The output level **must** remain constant during adjustment of frequency, and the adjustment must be smooth with no jumping about. Watch it on a scope! My experience is that the typical generator found in an undergraduate lab is barely up to the task, though my initial success was with such an instrument. *Highly desirable*: Tuneable/stable to 10Hz or better. Use a modern digitally-synthesised signal generator (such as the Fluke/Philips PM5136 or PM5138A. Agilent also seems to have a good series of function generators (although I have no personal experience of these)) and save yourself a lot of trouble!

Flask clamp: the strength of the acoustic resonance is sensitive to the way the flask is mounted - with our three finger clamp we found that the *loosest* grip gave the strongest resonance and brightest sonoluminescent light. A clamp with cork 'grips' seems to work much better than one with rubber-covered fingers.

Flask resonance: the acoustic resonant frequency of the flask decreases with temperature, falling by about 300Hz from room temperature to near freezing. I actually found two resonances, at 25.5kHz and at 25.1kHz - the former was stronger at room temperature, and the latter much better below 16C. The two resonances are probably specific to our flask.

Flask temperature: the water-filled flask has a fairly large thermal mass, so temperature-induced resonance variations are quite slow. Sonoluminescence is however much brighter at the lower temperatures - below about 10C is really quite bright. Much above 20C it becomes much harder to see the glow.

Bubble size: bubbles reach an equilibrium size for a given set of parameters. Other researchers have established that a sonoluminescing bubble cycles its size between about 50microns and 0.5microns with each acoustic wave.

Flash: Putterman et al report that the upper limit on the flash duration is 100ps, and at room temperature around 10^6 photons are emitted in each.

Measuring bubble size - Mie scattering

Mie scattering describes the interaction of light with an object whose dimensions are comparable to its wavelength. Integrated over a sufficient angular region, the scattered intensity is proportional to the cross section of the object. Hence by shining a light beam on one of our tiny bubbles, its radius can be monitored by measuring the amount of light scattered in a given direction.

Towards the end of my time on the experiment I built an op-amp amplifier for a BPX65 high-speed photodiode, and encased the diode and amplifier in a small die-cast box for electrical screening. With a solid-state laser beam focused on the bubble using a 2" focal length eye-glass, scattered light was collected by a 1" focal-length lens and focused onto the photodiode. Output from the diode amplifier was fed to an oscilloscope, giving a trace of scattered light intensity. With the well-focused beams, optical alignment was quite tricky, and results correspondingly variable. Nevertheless, it proved the idea and equipment worked, and excellent (qualitative) plots of bubble radius vs. time were obtained -- see figure 7. These results were completely consistent with those published by Hiller et al. With more time, careful setting up, and calibration, quantitative measurements could be taken, and relationships of bubble-size against water temperature, gas content, or drive level etc. could be investigated.

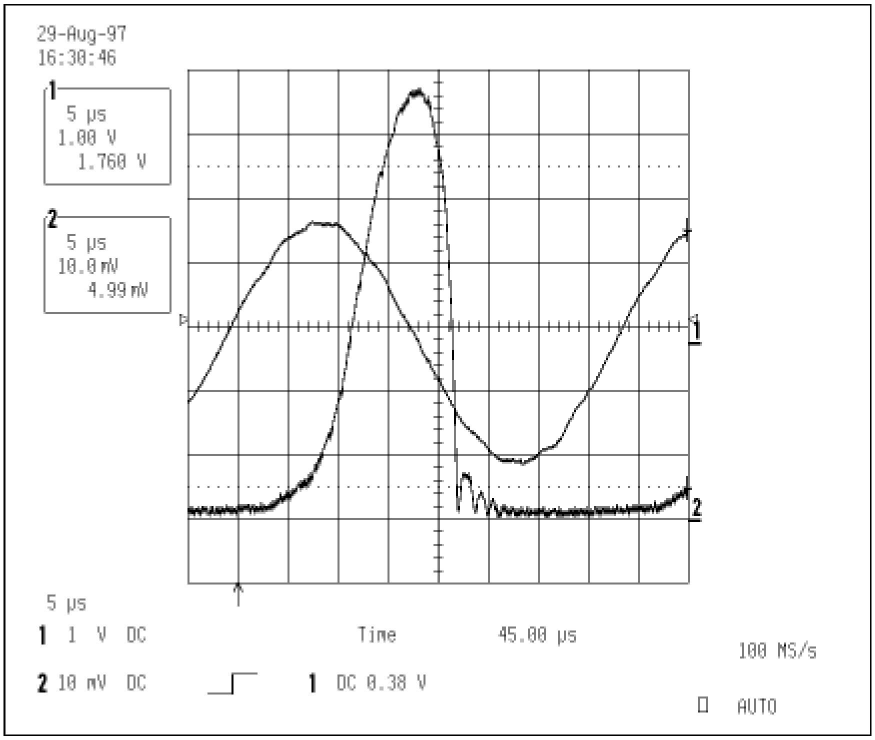


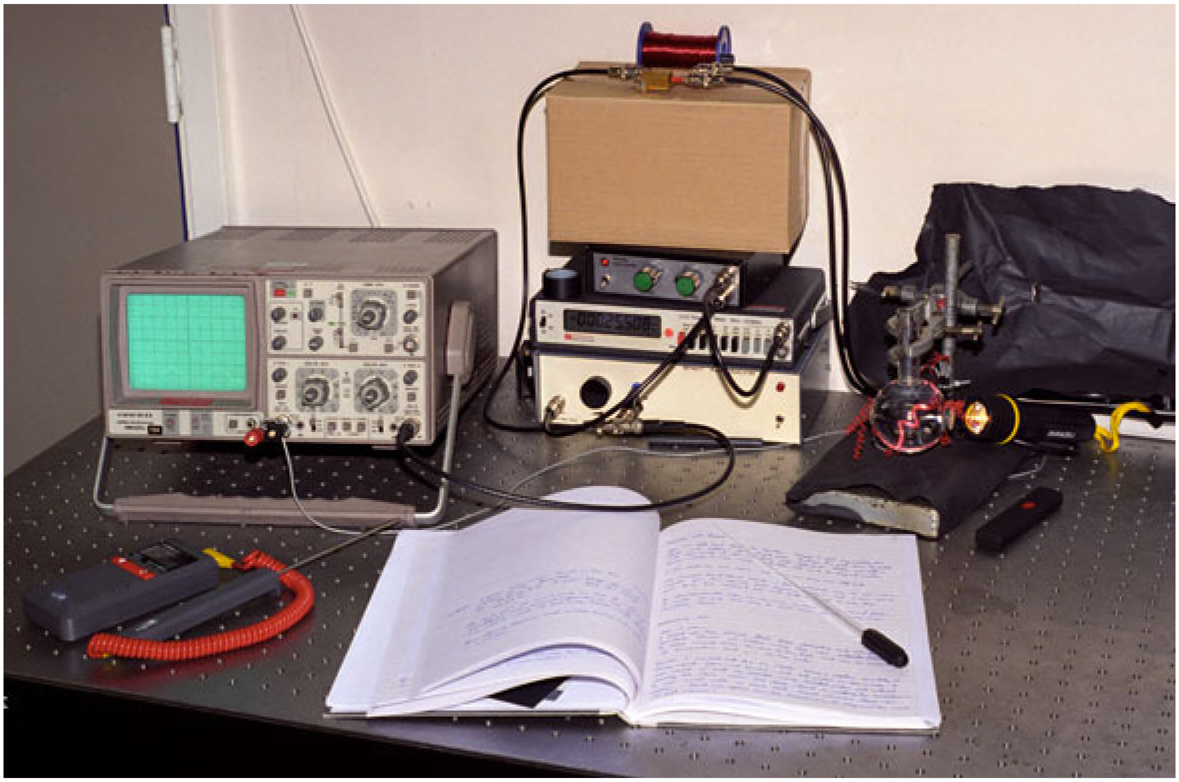
Figure 7: Oscilloscope traces showing: **1** the signal from the microphone attached to the bottom of the flask, and **2** photodiode signal for laser light scattered by the bubble (relating to bubble radius). I would like to emphasise that the Mie scattering results shown are **obtained from a single acoustic cycle**, and they are *real data* - not some theoretical best fit!!!

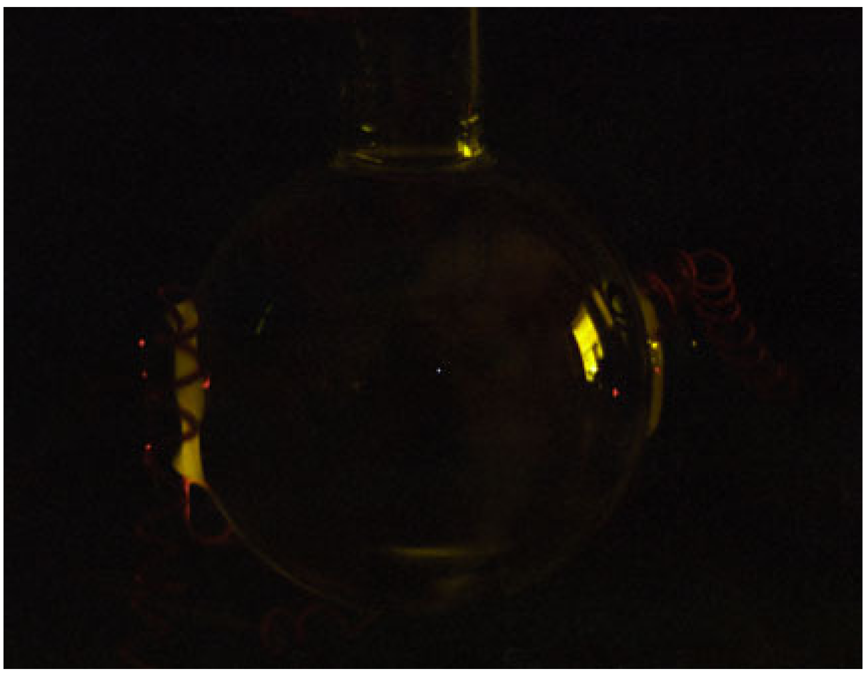
Conclusion

It was greatly encouraging to witness sonoluminescence relatively soon after commencing work on this project. After the initial success, the drive arrangements and signal generator were rapidly developed to improve the control and stability of the bubble. At first, the behaviour of the bubble seemed temperamental, but over the following weeks a 'feeling' for the setup was gained, particularly the recognising of characteristics due to different dissolved-gas concentrations and flask grip. Eventually, most phenomena were fitted into a wider picture and became explicable and reproducible.

Consistent with published results, the brightness of sonoluminescence was seen to increase as the drive level was increased, and as the water was cooled. Regrettably, but for largely logistical reasons, a photomultiplier or similar device for quantitatively measuring bubble intensity was not employed in this study. Despite its simplicity, the Mie scattering configuration set up in the final days of the project gave extremely promising results, with plots of bubble size against time being in almost exact agreement with those of Hiller et al., save for an absolute scale. With a little more care in setting up and alignment, and overcoming the problem of the bubble changing its position in the flask as the acoustic drive is increased, the measurements could be made quantitatively and more easily. This would enable the relation of bubble-size to water temperature, as well as drive-level, to be investigated.

Altogether I am confident that the requirements of the project brief have been excelled, with a reliable sonoluminescence apparatus constructed, the initial problems overcome, major characteristics verified -- and a great deal of expertise gleaned! I await with interest the results of subsequent studies.





Suggestions for future study

- Effect of magnetic field. What happens if the flask is placed between the poles of a large electromagnet? Is the light noticeably weaker/stronger in parallel- compared with perpendicular to the field? Is there any polarisation of the light (use a piece of Polaroid plastic)? If any non- isotropic characteristics can be induced, what might they imply about the mechanism of sonoluminescence?
- Design and construct a more permanent and better-aligned Mie Scattering set-up. Investigate dependence of bubble size/rate of collapse on water temperature as well as drive level. One problem that needs to be overcome is that the bubble moves slightly in the flask as the drive is varied. It *may* be

that little more than careful tuning of drive frequency is required?
- Set up the flask inside a darkened enclosure and use a photomultiplier to measure the time-*averaged* bubble intensity. Time-*resolved* study of the flash would require an *optical* oscilloscope ($$$ - and would seem unlikely to reveal much not already known).
- Use a suitable spectrometer to measure the (not time-resolved) spectrum of the light from the bubble. Does it vary with the brightness (drive level or temperature)?
- "Close" the system. With the SL flask forming part of a sealed system, the amount of dissolved gas could be both controlled and measured, and gases other than air could be tried. You will need to investigate means of connecting gas/vacuum systems to the flask without seriously affecting the acoustics, and remote ways of seeding bubbles (I'd try the electrolytic approach). Degassing the fluid by vacuum rather than boiling should enable a wider variety of other solutions to be tested.
- Piezo transducer mounting. It is awkward to wash out the flask thoroughly (essential if trying a variety of solutions) with the transducers attached. Can some kind of removeable/clip-on mounting system be devised for them?

Acknowledgements

Many thanks are due to my supervisor, Dr Nigel Mason, and to all the inhabitants of the Molecular Physics Lab who put up with my vocal excitement and persistent turning off of the lights!

Appendix

Supplementary electrical information

The simplest measure of amplitude when reading a waveform on an oscilloscope, used throughout this document, is the **peak-to-peak voltage**, (**V_{p-p}**), shown in figure I.

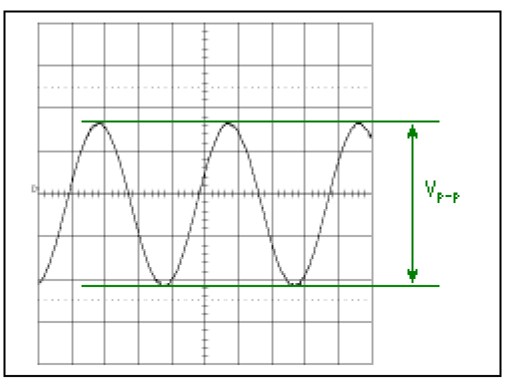


Figure I: Definition of peak-to-peak voltage measurement

The *peak* voltage is half the peak-to-peak, and for a sinewave, the r.m.s. voltage is 1/sqrt(2) times V_{pk}. Therefore,

$$V_{rms} = V_{p-p} / (2 \text{ sqrt}(2)) \quad .$$

Assuming the voltage and current flowing in a circuit are *in phase*, the power dissipated is equal to the product of r.m.s. current and r.m.s. voltage.

Hence

$$\text{Power} = V_{p-p} \times I_{p-p} / 8 \quad .$$

When the voltage and current are *displaced* in phase, for example the high-voltage side of the transducers, driven through the inductor, a phase factor would have to be used to calculate power. Failure to correct for phase shifts in calculation usually leads to the false result that an unrealistically large amount of power is consumed.

High-voltage measurements

If possible, use a special high-voltage oscilloscope probe to measure the voltage on the transducers. If a probe is not available, then a potential divider can be made using resistor, but it should be borne in mind that standard resistors have a maximum working voltage of around 250V (and will permanently change their resistance if this is exceeded). A chain of 4 2.2MOhm resistors for the top-side, and a single 8.2kOhm for the bottom-side, will give approximately divide by 1000 [in reality, 1074].

Constructing a suitable inductor

A series inductance of around 30mH is required for the transducers, and it must have a fairly high Q and be capable of carrying a couple of hundred milliamps. Such inductors are not available as off-the-shelf parts from the general electronics supply companies. I used what was left on a 500g spool of 0.5mm dia. enamelled copper wire (perhaps 150g of wire?), tuned by sliding a ferrite rod (sold as MW/LW radio aerial) down the centre of the plastic spool. Use a wide-range frequency generator to find the electrical resonance with the transducer - if it's too low (say below 27kHz with the rod removed), remove some wire, if it's too high (say above 24kHz with the rod inserted) then add more wire. The rod should change the frequency by a factor of two, so getting the inductor right isn't too difficult. For the given spool size, a 3" long ferrite rod works well - but again the length isn't too critical. A longer rod will lower the resonant frequency further, but leads to a slightly poorer Q -- a weaker resonance.

Reports are abound (on the Internet etc.) that sonoluminescence requires at least an 100/200/300... Watt amplifier. In fact typically only ONE watt is dissipated in the transducers/drive system during sonoluminescence. More "powerful" amplifiers are really only being used to overcome bad matching by brute force, by providing more raw voltage swing - it's not the available power that counts!

Because the relation between amplifier output and acoustic energy in the flask is so dependent on the drive and its tuning up, I always quote the sound level in terms of microphone level - which directly indicates the sound level in the flask.

SAFETY NOTE

The junction between the inductor and transducers will exhibit a potential of order 250V AC (25kHz) when the system is tuned up and at sonoluminescing levels. Take care not to touch anything at this point in the circuit when the volume is up! The 'live' side of the transducers are connected with a red wire, and the corresponding silvered side of the transducer is stuck towards the flask. DO NOT transpose the drive wires at the BNC connections, otherwise the EXPOSED side of the transducers will become 'live'. Similarly, avoid touching the tips of the spare red wires from the transducers, and the live connection to the inductor - they deserve some respect!

Post-Script

Since this document was originally composed, an undergraduate student has spent two terms on the project. In the course of their studies, we found that the sphericity of the flask is very important. If there is more than a millimeter difference between polar and equatorial diameters, then the resonance becomes very much broader and less strong, requiring more electrical drive to achieve the same sound intensity in the flask.

We always knew the available electrical drive with the set-up described was only just sufficient, but we have since found that a "universal-type 100V line transformer" can be used successfully to help match the output-impedance of the amplifier to the inductor/transducer circuit: **if** more power is required (and remember you can have too much power!), connect the amplifier output between the "speaker" side 0v and 4ohm connection, and connect the inductor to the 8- or 16ohm connection - with the transducer or 1ohm resistor going to the 0v connection... **all on the same side of the transformer** (we're using it as an *auto*transformer). Don't touch the other side of the transformer (the 100V-line side) as these windings will exhibit a very high voltage when the circuit is energised.

The **transducer set** are available from:

> Channel Industries
> 839 Ward Drive
> Santa Barbara
> California
> Tel: [US] (805) 967 0171
> Fax: [US] (805) 683 3420

Sonoluminescence FAQ

[May 2007] I've just begun assembling a sonoluminescence FAQ, which should prove useful to anyone trying to reproduce the work here.

Sonoluminescence FAQ

The work described here was performed on behalf of, and funded by, the undergraduate teaching laboratory in the Physics Department of University College London.

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