Demonstration comparing sound wave attenuation inside pipes containing bubbly water and water droplet fog

Timothy G. Leighton,[a] Jian Jiang, and Kyungmin Baik
Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom

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This paper describes a demonstration and explanation of sound absorption in water due to bubbles, and in air due to a fog of water droplets. It is suitable for 10–12 year olds, but the paper indicates where further exploration of the simplifications in the explanations provided for that age range would allow the demonstration to be used for undergraduate and Masters-level teaching. Applications to submarines, the space shuttle, and neutron generators are described. The demonstration is designed for transportation in a family-sized car. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3676732]

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I. INTRODUCTION

An experiment was devised to teach about sound waves and absorption. This was done by projecting the same chirp upwards in two adjacent pipes, one filled with air and one filled with water. In both pipes, an acoustic source is placed at the base of the pipe, and an acoustic sensor at the top. Air bubbles are then injected into the water-filled pipe, and dry ice fog (consisting of water droplets) is introduced into the air-filled pipe. Attenuation is observed in both pipes by looking at the sensor output on oscilloscope screens, and listening to it through earphones or a class loudspeaker. Explanations suitable for 10–12 year olds are outlined, although the experiment contains sufficient complexity to enable, through further questioning, an undergraduate- or Masters-level class to learn through exploring the simplifications in the explanation given to children.

The experiment has tested well on audiences of children, lay people and students of physics and engineering. It was designed to be loaded into a family-sized automobile and transported off site to provide a traveling demonstration, and has performed well as such, including featuring in a science/engineering program on national television in the UK.[1]

II. APPARATUS

Experiments are carried out in two Poly (methyl methacrylate) (PMMA) pipes of 2 m length, 4.445 cm inner radius, and 0.5 cm wall thickness. The two pipes are placed side-by side, held upright by wooden supports clamped to a workbench (Fig. 1). The base of the water-filled tube is sealed using a 3 mm neoprene membrane, clamped between two 1-cm thick PMMA plates, each with a circular hole of 4.445 cm inner radius in their center that aligns to the bore of the pipe. The upper such plate was glued to the base of the pipe, and then the neoprene membrane was sandwiched between the two plates that were clamped together to make a water-tight seal. The base of each tube was raised some 30 cm from the floor using a wooden frame. The pipe on the left was to be filled with water, and beneath it was placed a bucket or trough, of sufficient volume to hold the contents of the water-filled pipe should it leak. Into this bucket was placed the sound source for the underwater signal. In this case a sonar source (4008-00-01-A, produced by Neptune Sonar LTD.) was used, which has a usable frequency range of 10 kHz to 30 kHz. Provided that they emit suitable frequencies (audible sound above 10 kHz—see below), several commercial underwater sound sources are available (such as the AQ SUB-AQUA 30 underwater speaker), and indeed inexpensive ones can be made from loudspeaker tweeters that have been waterproofed with aircraft dope.[2] However, these home-built sources do not have as long a lifetime as commercial devices and, as with all the electrical apparatus here, must be electrically safe particularly considering the possibility of submersion or condensation. If sources small enough to be submerged in the tube are found, the base of the tube may be sealed with a less complicated arrangement. The tube was filled to a depth of 1.8 m with tap water, and a hydrophone was placed 10 cm below the top of the water column. Here a B&K 8103 hydrophone was used, although (depending on the power output of the sound source) an inexpensive alternative can be made from a loudspeaker tweeter,[2] suitably waterproofed and made safe, and electrically screened. This is because, as with all in-water acoustic sensors and particularly with home-built hydrophones, when a signal has been detected the sensor must be taken just out of the water to check that the signal disappears because the air introduces a significant acoustic impedance mismatch. If it does not, the signal detected by the sensor might in fact be direct electrical pickup of the signal that is provided from the power amplifier to the sound source (the two will have similar characteristics).[3] A lightweight open frame (e.g., a bamboo X-frame) at the top of each tube ensures that the acoustic sensor is stationary on the pipe axis.

The signal from the hydrophone was conditioned by a preamplifier (Brookdeal Precision AC Amplifier 9452, which could also perform as an analogue filter) and acquired

[a]Author to whom correspondence can be addressed. Electronic mail: tgl@soton.ac.uk

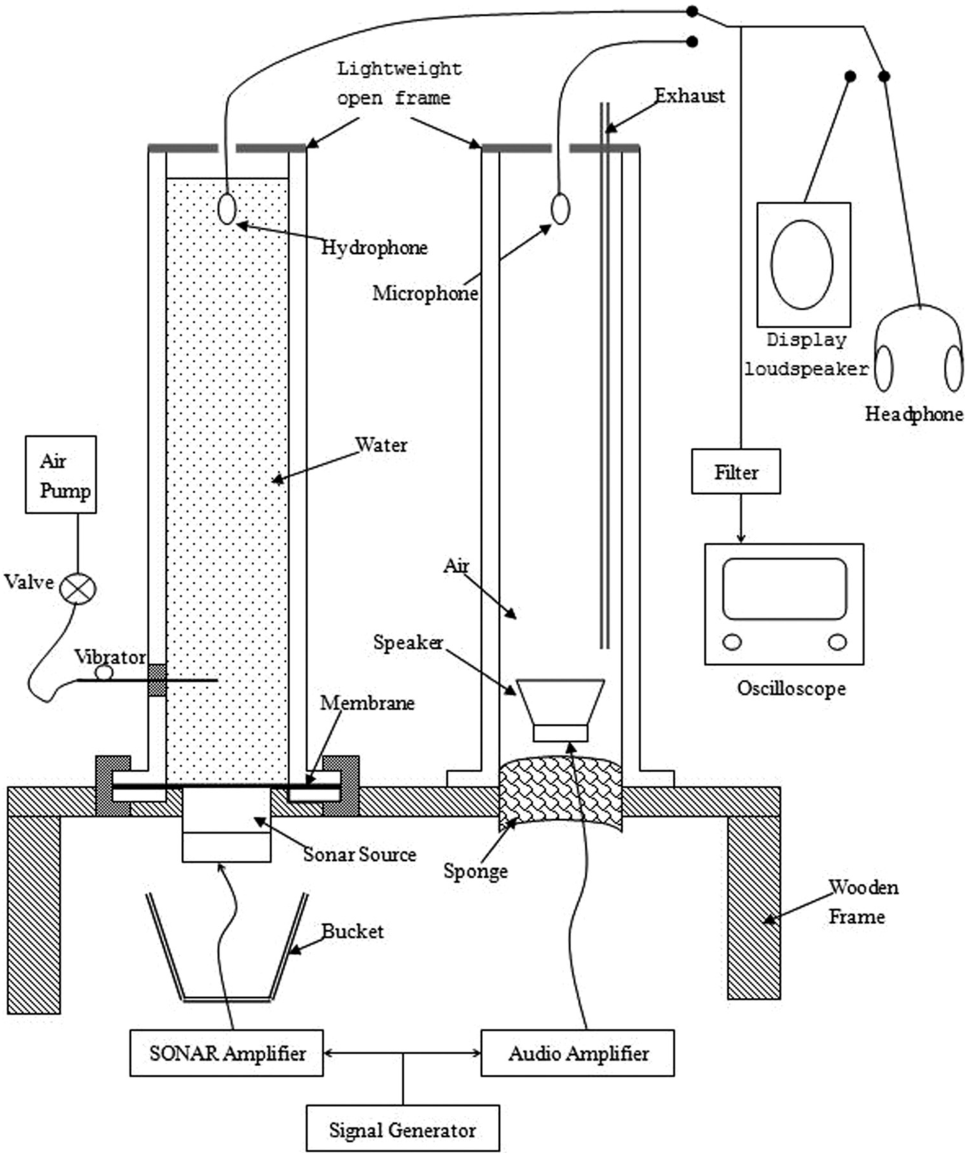

FIG. 1. Schematic of the test rig.

by oscilloscope (LeCroy 9304 C). It was also amplified and played through a loudspeaker for the audience (although with a small number of listeners, earphones are better since they remove the problem of feedback which can occur if this loudspeaker is too close to the hydrophone, an effect which can be even worse with the in-air microphone placed in the other pipe).

The layout of the air-filled pipe was very similar to that of the water-filled one. Indeed, it was designed in order to provide a back-up for the water-filled tube were the latter ever to leak (allowing a simple swap to be conducted without significant delay, since such demonstrations must usually work on time when the audience has gathered, and the apparatus was designed to travel for shows far from the home laboratory when spares could be held). A loudspeaker (ALTAI 340 M, 8Ω) was chosen as the in-air sound source at the base of the air-filled pipe. There are many mounting options, the chosen one here being to roll sponge around the cable to the source and then squeeze this sponge into the base of the pipe.[1] At the top of the tube was placed a microphone, which was capable of monitoring sound from 20 Hz to 20 kHz in air. The microphone output was then conditioned by the same preamplifier as was used for the hydrophone, and displayed on the oscilloscope and played through the display loudspeaker/headphones.

The same signal was applied to both sound sources. The one chosen was an upwards linear chirp sweep from 10 kHz to 20 kHz (Fig. 2) since it was sufficiently high to produce attenuation that could be heard by the listeners, but not so high as to be difficult for a wide age range of listeners to hear. The chirp is repeated every second to facilitate the audience in hearing the changes due to addition of bubbles/droplets. Whilst the apparatus could readily be adapted to measure the effect of bubbles/fog on group velocity using shorter pulses, that was not the intention with this young audience. The long signals used here set up reverberant sound fields (which could be used to determine phase speeds, but this was not done with the young audience). The amplitude of the field at the location of the sensor was dependent on both the mode shape as the frequency rises, and the

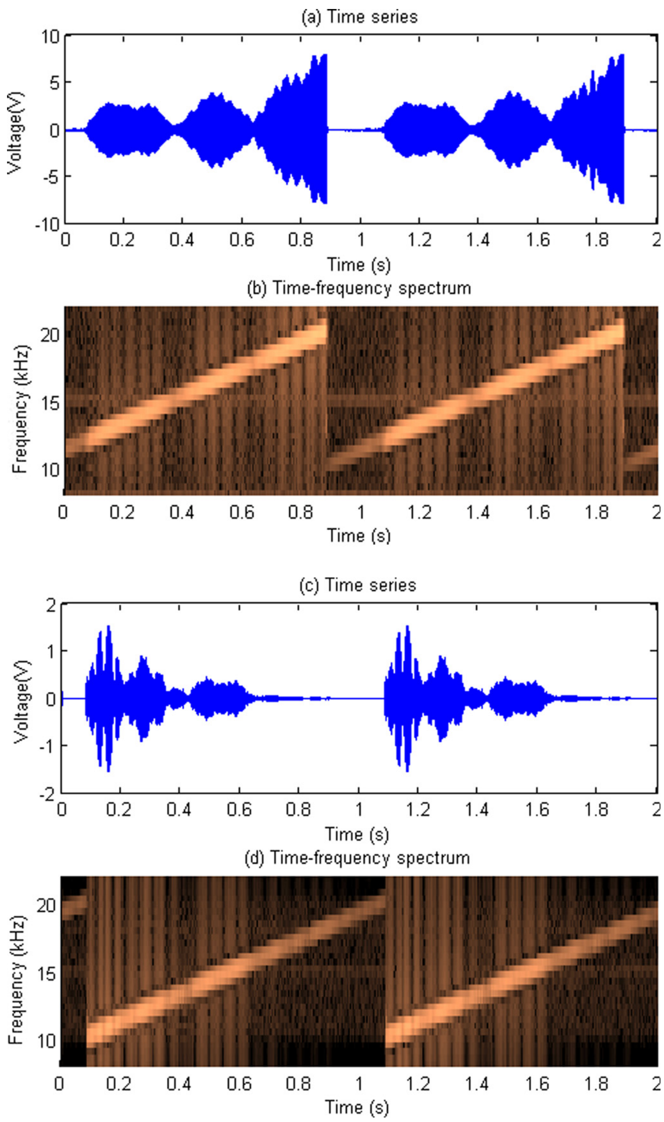

FIG. 2. (Color online) Two transmissions (spaced 1 s apart) of the chirp sound covering the frequency band from 10 kHz to 20 kHz. Signals shown in this figure are: from the hydrophone in the water-filled pipe before the addition of bubbles [(a) time series and (b) time-frequency plot]; and from the microphone in the air-filled pipe before the addition of fog [(c) time series and (d) time-frequency plot]. In free field the source has a relatively flat frequency response over this range, and minima in the envelopes of (a) and (c) occur at those frequencies where the reflection from the upper end of the pipes creates destructive interference at the location of the sensor. The propagating axisymmetric modes have been characterized in the liquid-filled tube (Ref. 17).

frequency response of the sound source (a much lesser effect with the apparatus we used).

A sonar amplifier (B&K Power Amplifier Type 2713) and an audio amplifier (Cambridge Audio, A1 Integrated Amplifier) were used to adjust the strengths of source signal to make sure they were strong enough to be clearly detected by the hydrophone (and heard by the audience) in bubble-free conditions, and the microphone in droplet-free air.

Bubbles are introduced by a standard bone marrow biopsy needle (BD408627; a standard hypodermic needle will do), inserted through a bung into a 1 cm diameter hole drilled into the pipe wall 20 cm from the base of the pipe. Using an on/off flow switch placed between the needle and pump, a few seconds of air flow is pumped through the needle. Whilst an aquarium air pump (Rena Air-200) provides satisfactory results, an air compressor (Clarke, WizAir) was more spectacular (although if too much air is pumped in, splashing occurs). However, absorption by bubbles is not efficient if the bubble diameter D is larger than the size which is resonant with the frequency f of the sound field. The rule-of-thumb[4,5] for air bubbles in water under 1 atm of static pressure is $[D/\text{mm}] \times [f/\text{kHz}] \sim 6$, implying that this experiment requires bubbles with diameters of around half a millimeter or less. Details of the exact relationship[6] for air bubbles in water vary with surface tension, bubble size, atmospheric pressure (it is good practice to keep note of the latter when taking measurements like this[7]), and more subtle factors such as confinement within a pipe,[8,9] but such details are not required for the intended audience.

Injection of such small bubbles into still water is not simple. The addition of a small amount surfactant to the liquid can help, but too much generates frothing. With small air flows, such as the aquarium pump generates, the bubbles will be too big from a needle injecting into still water, and this is rectified by vibrating the needle (Fig. 3; see also the video at the web page[10] associated with this article). This can be done in a simple and inexpensive way by attaching the vibrator from a mobile phone to the needle using epoxy. When supplied with 2 V the needle vibrates at 150 Hz, rising to 200 Hz with a 3 V supply. It is commonly thought that reducing the bore of the needle will generate smaller bubbles, but this is not so because, without vibration, the smaller bubbles remain close to the needle tip and coalesce with the successor bubbles that are growing from the needle, so that the bubble which eventually travels into the liquid is large[11] (Fig. 4). If sufficient gas flow can be safely provided (here up to 4.5×10^{-4} m^3 s^{-1} by the aquarium pump, and up to 7.5×10^{-4} m^3 s^{-1} by the air compressor), then a few seconds of flow will flood the tube with bubbles, the largest of which will rise rapidly under buoyancy, leaving the smaller bubbles present to provide effective absorption. Indeed, one of the most startling observations of the audience is that, tens of seconds after the gas injection has ceased, when there are barely any bubbles visible in the tube, the attenuation is still great, and only when the last few tiny bubbles have risen to the top of the tube (which can take over a minute) does

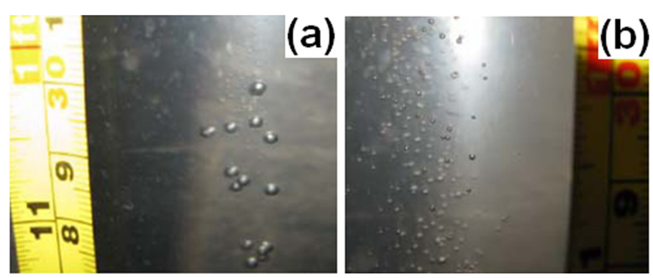

FIG. 3. (Color online) For constant air flow settings, the bubbles generated by the needle before the vibrator is turned on [frame (a)] are much larger than those generated when the vibrator is activated [frame (b), which has a similar scale (shown) as (a)]. A movie of this, and the effect on attenuation can be found at the associated web page (Ref. 10). See supplementary material (Ref. 46) for this movie.

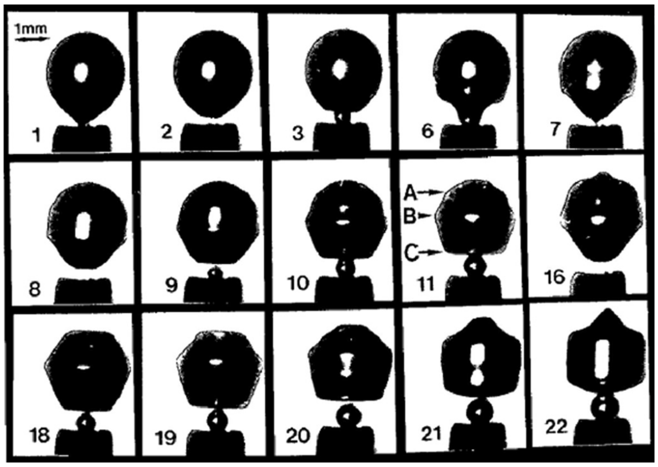

FIG. 4. Selected frames from high speed footage (filmed with an interframe time of 0.24 ms) showing how a bubble released from a metal nozzle (frame 1) does not rise rapidly enough under buoyancy to escape from coalescence with successor bubbles (frames 3, 10, 22) growing at the nozzle tip. In this way, only bubbles which have grown sufficiently large to have a great enough buoyant rise speed to escape from this coalescence, are released into the body of the liquid. The bubble shape mode gives the appearance of ripples (e.g., peaks A–C) moving over the surface of the bubble. From Ref. 11.

TABLE I. Suppliers for material and equipment used in the demonstration.

	Website
PMMA tube	http://www.clearplasticsupplies.co.uk/
Neoprene membrane	http://www.maclellanrubber.com/
Vibration motor	http://www.uk-mobilestore.co.uk/
Standard hypodermic needle	http://www.medisupplies.co.uk/
Exhaust hose	http://www.diy.com/
Underwater sound source	http://www.aqudos.com/
Other electronic equipment:	http://www.bksv.com/
(Signal generator, Hydrophone, Power amplifier, Preamplifier, Oscilloscope, Loudspeaker, Microphone, Audio amplifier)	http://www.electronics.globalsources.com/
Air compressor/Air pump	http://www.machinemart.co.uk/
Dry ice	http://www.dryiceuk.co.uk/

the signal level return to normal (see the video at the associated web page[10]).

The fog is introduced into the air-filled pipe by pouring about 500 ml of hot water from one jug onto about 500 ml of dry ice which is held in a second jug.[1] This should be done by someone standing on a safe platform so that they can then pour the fog (produced by in the second jug) into the top of the air-filled pipe. This needs to be done with caution, as both hot water and dry ice can cause burns, and jugs which are insufficiently robust can fracture after a few thermal cycles (so that metal jugs are preferably to plastic ones).

For the fog to flow easily down the pipe, the displaced air must be allowed to leave it via an exhaust. If the air-filled tube has a hole at the base drilled for the needle bung should it be required as a replacement for the water-filled tube, this can be used. If not, a hose of 8 mm inner diameter can run up the inside of the PMMA pipe from its base to terminate about 10 cm above the top of the PMMA pipe (a transparent plastic tube removes one source of visual distraction from the audience).

A list of suppliers for the material and equipment used in this demonstration is given in Table I.

III. PROCEDURE

The procedure for the demonstration is simple, and similar for both pipes. We usually start with the water-filled pipe demonstration as the effect is more dramatic and provides the audience with cues to follow during the subsequent demonstration with the air-filled demo pipe. However this paper will first explain the protocol for the fog-filled pipe, as this is simpler.

The sound source is started, and the audience hear (and observe on the oscilloscope) the audible signal. With the air-filled pipe, the fog is generated and poured from the jug into the pipe. The amplitude of the signal falls on the oscilloscope screen, and the audience hears the drop in amplitude. The fog usually persists for a minute, depending on the exhaust—indeed if the latter is inefficient, the fog may need to be blown from the tube (e.g., with a hairdryer). The effects are modest, which is why it is better to start with the water-filled tube.

The injection of bubbles provides a more complicated set of phenomena, and it is worth doing this demonstration slowly, and perhaps repeating it, before proceeding to the simpler fog demonstration. There are two options for treatment of the hydrophone signal when demonstrating the effect of bubbles to the audience. Our preferred method is to ensure that the input to the oscilloscope goes through a 10 kHz high pass filter, but that the input to the display loudspeaker (or earphones) does not [Figs. 5(a) and 5(b)]. If the audience needs a simple message, the signal to the display loudspeaker can also be passed through a high pass filter, but whilst that makes the simple absorption message more tractable, it deprives the audience of the spectacular injection sounds and hides the fascinating physics behind this (these sounds can be found at the associated web page[10]). Hence the authors usually introduce a high pass filter to the oscilloscope input (without this, the injection sounds dominate the signal) but have no filter to the display loudspeaker input. That way, when the bubbles are injected, the audience can hear the sound generated by the bubble injection, and furthermore can hear that the rising bubbles effectively produce a shorter "organ pipe" for the sound, generating a note which rises in pitch as the bubbles rise [Fig. 5(c)]. This spectacular sound can be used to explain a great deal of physics, from the formation of modes in the pipe to the way the bubble cloud produces an impedance mismatch, as does the upper air/water interface, so that sound reflects strongly between the two. Indeed, depending on the bubble cloud injected, slug flow and buoyant sorting of bubble size can be demonstrated. However, such exploration would, on first introducing the audience to the demonstration, distract them from the central message, which is the very effective absorption introduced by the bubbles. Therefore, we usually explain them the second or third time bubbles are injected and, if couched in suitable terms (relating to organ pipes and the sizes of musical instruments in the same family, or the audience's

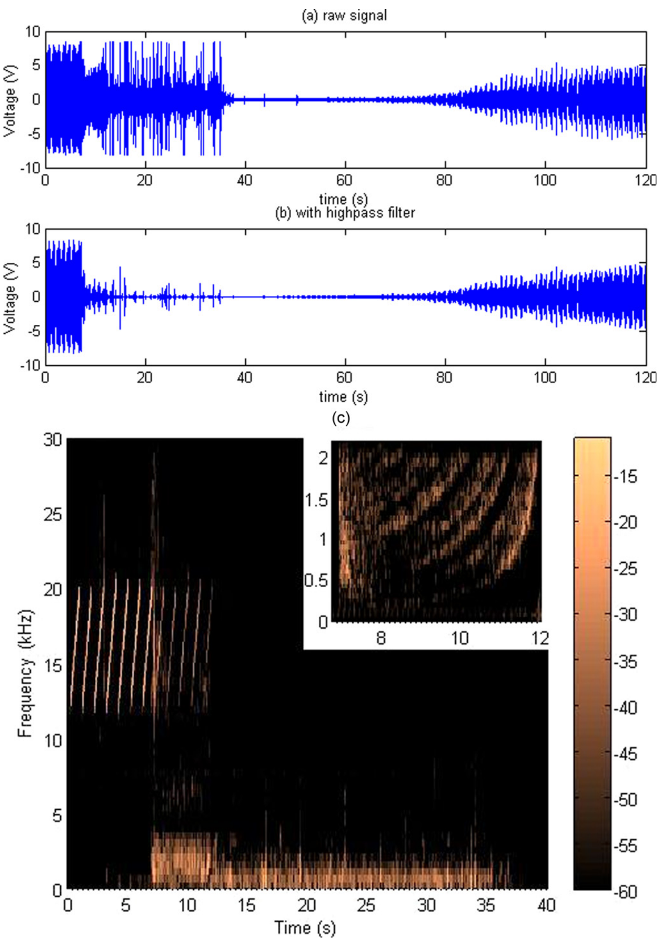

FIG. 5. (Color online) Hydrophone data. (a), (b) The hydrophone signal from the water column, (a) being the full spectrum data and (b) being the signal after filtering by the 10 kHz high pass signal. Bubble injection began at time $t \sim 7$ s and the valve was closed over the 3 s from ∼35 to 38 s. (c) A time-frequency spectrogram of the data in (a). The chirps are clearly visible until $t \sim 7$ s, but after that are increasingly attenuated as more bubbles are injected into the pipe, such that after around $t = 13$ s only the bubble noise is detectable. The insert overlying the upper right corner of this plot shows, with the same dB greyscale, a high-resolution detail of the low-frequency (< 2 kHz) section of this plot for ∼5 seconds after the bubbles are first injected. The inset clearly displays the rising notes that can be heard as the rising bubbles effectively shorten the length of the "organ pipe" above them. See supplementary material in Ref. 46 for the sound file of the data in (a), and for the equivalent sound file when fog is added to air. These sound files can also be found at the web page (Ref. 10) associated with this article.

experience with echoes of sound in air of one density from room walls of a different density), such explanations can be made tractable for 10 year olds.

Once they have taken a few seconds to respond to the rising organ pipe note, before explaining how that occurs, the demonstrator should point to the amplitude of the signal on the oscilloscope trace, and then ask the audience to listen to the reduced loudness of the chirps. They should then note how very slowly the signal amplitude returns, even though visually most of the bubbles have risen out of the tube in seconds (see the movie at the website[10]). This is explained to the audience because the most effective absorption comes from the small bubbles that are resonant with the chirp frequencies, and these small bubbles rise more slowly than the larger bubbles to which the eye is drawn.

In summary, the preferred protocol is to high pass filter the oscilloscope signal but not the display loudspeaker/earphone signal, inject bubbles once and draw the audience attention to the reduced absorption. Wait to demonstrate how long it takes the signal to return to full strength, even though only a few small bubbles have yet to rise out of the pipe. Then ask them to recall the rising note, explain where that comes from in terms of the acoustically reflective rising bubble cloud shortening the length of the "organ pipe," and then inject bubbles again. When they are happy with this demonstration, move on to the air-filled pipe, and show them that the fog is less effective than the bubbles at absorbing the sound. Then explain why, in terms of the mechanisms discussed in Sec. V.

IV. RESULTS

Figures 5 and 6 show the output of the hydrophone during the demonstration. Sound files of the hydrophone and microphone data to accompany these figures can be found at

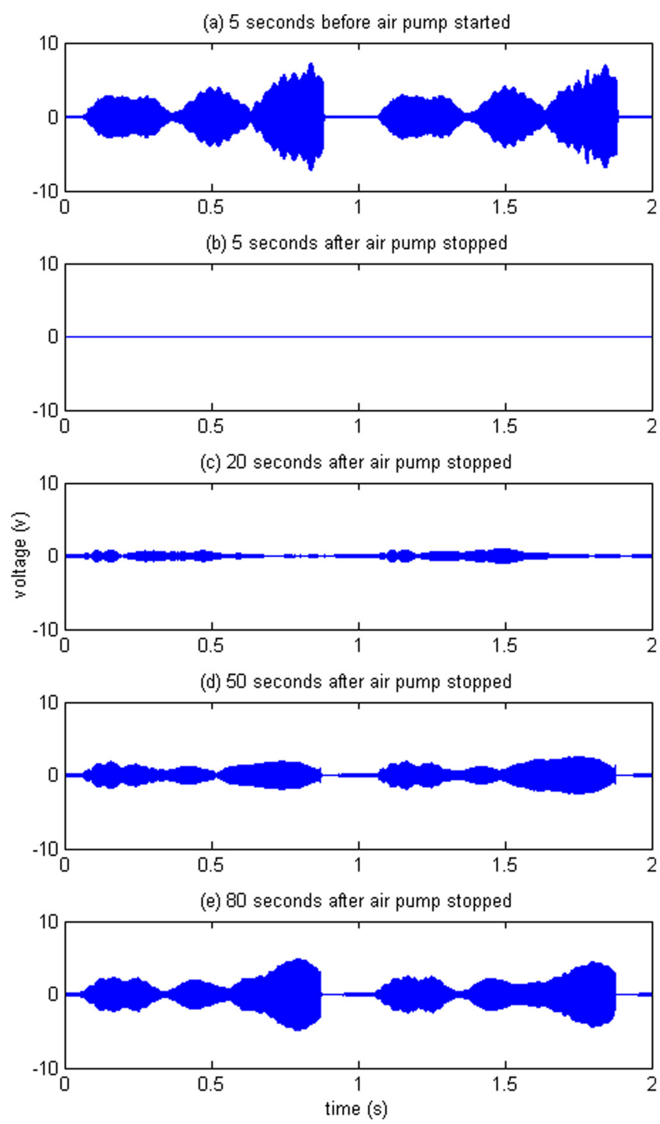

FIG. 6. (Color online) Hydrophone signal shown on oscilloscope, corresponding to the times t in Fig. 5 of (a) 2 s, (b) 43 s, (c) 58 s, (d) 88 s, (e) 118 s (times of pump on/off are ±0.5 s).

the associated web page.[10] Figures 5(a) and 5(b) show the recorded hydrophone signal with and without a high pass filter. Note that the time scale covers 2 minutes, and so because the chirps of Fig. 2 are repeated every second, the gaps between the chirps are barely visible on this scale. If the high pass filter is not used [Fig. 5(a)], the attenuation of the chirp during the injection period is very difficult to discern in the time history because of the sound generated by the bubble injection (at time $t = 7$–38 s). However, as the web page shows, the accompanying sound file is spectacular and, as explained in Sec. III, demonstrates the interesting physics of a water-filled organ pipe effectively shortening in time due to rising bubbles. Hence, the filter is used but only for the signal shown on the oscilloscope. Figure 5(c) is a time frequency plot of the data from Fig. 5(a), and readily reveals both the chirps, the bubble noise, and (inset) the rising note associated with the "shortening organ pipe" effect.

Figure 6 shows the hydrophone signal in the water-filled pipe, displayed on the oscilloscope screen after first being high pass filtered. Bubble injection started at $t = 7$ s and stopped at $t = 38$ s. Before injection [Fig. 6(a), $t = 2$ s], the chirp pulse is visible, repeated every second. Immediately upon injection the amplitude of the signal decreases, and only slowly returns as the bubbles rise out of the water column under buoyancy [Figs. 6(b)–6(e)]. When the signal is at its minimum value, it is 40 dB less than the value prior to bubble injection.

Figure 7 shows the microphone signal in the air-filled pipe, displayed on the oscilloscope screen at time (t) relative to when the fog was poured into the pipe. Before fogging [Fig. 7(a)], the chirp pulse is visible, repeated every second. The amplitude of signal decreases to a very small value after fogging and returns back as the fog gradually disappears [Figs. 7(b)–7(e)]. When the signal is at its minimum value, it is 30 dB less than the value prior to fogging.

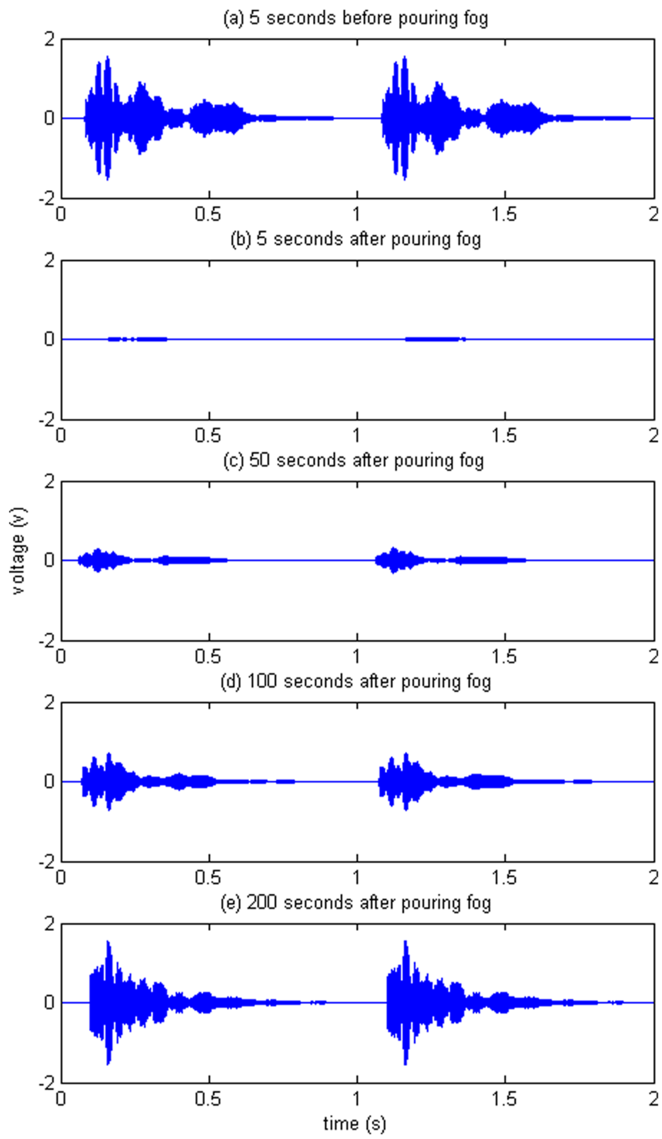

FIG. 7. (Color online) Microphone signal shown on oscilloscope.

V. DISCUSSION

This demonstration is intended for a younger science or lay audience, and so the explanations are qualitative (although more detailed explanations are available in the literature, for acoustic absorption,[12–15] propagation in pipes,[16,17] and losses due to bubbles,[5] water droplets,[18] and other particles in suspension[19–21]). Test audiences aging from 10 years old to mature lay members of the public have appreciated the following explanations. Fundamental to the understanding of these explanations is that sound waves consist of local back-and-forth vibrations in the fluid (liquid or gas), which give rise at any given location to cyclic pressure fluctuations (such that the pressure at any point in the liquid varies from high pressure to low pressure, and back again, many times each second). Also, the audience should be told that the absorption of sound waves is, in effect, converting mechanical energy ultimately into heat.

It is best to first explain the attenuation of the signal by fog. A vertical up-and-down "oscillatory karate-chop" oscillation of the right hand is used to mimic the back and forth oscillation at a point in the gas, as caused by the sound wave. Children can mimic this. Then say that if this oscillating region of gas is next to another region of gas of the same density, the two regions move together with little slip because they have the same density. This can be illustrated by taking the left hand and placing it against the right hand as it does its oscillatory karate-chop motion, and let both do the oscillatory karate-chop motion together, touching but not slipping (which children can also mimic). Now say that if the oscillating gas is next to a drop of water in the fog, the water is denser than the gas and so the moving gas cannot drag it with it, and the two rub together and frictional heating occurs. This converts the mechanical energy of the sound wave into heat. This is illustrated by balling the fist of the left hand to represent the water drop, and bringing it up against the right hand as it undergoes its oscillatory karate-chop motion. The balled fist does not move up and down, so the right hand rubs up and down against it, repeatedly, and generates heat through friction. Additional complexities (such as the ability of a higher concentration of carbon dioxide to increase acoustic absorption) are not suitable for a young audience, but could be explored with undergraduates.

The explanation of the absorption caused by bubbles is slightly different. The audience will understand that something similar occurs, because the gas bubble and the water are of different densities. But then point out to them that the absorption generated by the gas bubbles was much greater than that generated by the fog (they will have seen that on the oscilloscope screen and confirmed it with their ears). This is because an extra mechanism for absorption occurs with the bubbles. Remind them that the sound wave generates, at a given point in the liquid, a pressure fluctuation as well as an oscillatory motion. Given little prompting, the audience should work out that the high pressures will squash the bubbles, and that squashed gas gets hot (which is why a bicycle pump gets hot when they pump up their bicycle types). This is a good example of how bubbles convert the mechanical energy of the sound wave to heat, and so absorb the sound more effectively than can the fog (because water droplets are harder to compress than is the bubble gas).

This explanation is designed for younger audiences, and of course there are many details which would not satisfy more perceptive scientists and engineers. For them, therefore, a useful exercise is to ask them to criticize the above explanation. Prompts for increasingly sophisticated audiences might be (in approximate order of complexity): "won't the bubbles cool down when they expand, and therefore draw heat out of the water, so that no net heat enters the liquid?"; "won't absorption come from the cyclical temperature changes in the air as the sound wave passes through it, which cause heat transfer between the air and the water droplets next to them (which have a higher specific heat capacity) and so absorb energy from the wave in air?"; "isn't it the case that the simple explanation that 'high pressures will squash the bubbles' only works if the bubbles are smaller than resonance, because if they are larger than resonant size their motion will have gone through the Pi phase change at resonance and they will expanding under compression?"; "does evaporation occur and contribute to cooling?"; "what roles do the time lags in heat transfer between gas and liquid play in damping?" These questions, and those raised by the audience, can take this simple demonstration, designed for children, and use it as a high-level teaching tool.

With all audiences, it is important to discuss the applications of these studies, and these applications can be tailored to suit the audience in question. Absorption by water droplets is exploited[22] to reduce the sound reflected off the ground by the Space Shuttle when launched,[1] as this can damage instruments, although other effects (such as the entrainment of the liquid into the flow and its evaporation) are also important.[23–25] This is because the reduction of the sound source level of the jet (by decreasing jet transfer through momentum transfer between liquid and gaseous phases, and reduction in jet temperature through partial vaporization of the water)[26,27] are probably more important than the acoustic absorption that occurs during transmission. Literature features many poetical and fictional descriptions of how sound is changed in fog, although these perceptions also rely on more effects than are demonstrated here. Sound absorption by bubbles has been exploited by incorporating gas pockets into the rubber lining placed on submarines (Fig. 8). This reduces their "visibility" to active sonar, so that it is more difficult for ships to find them through echolocation.[1] Such sound absorption is also being developed to reduce the damage by shock waves in the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (Tennessee),[28–30] and indeed the water-filled pipe described here has been used directly for such work.[1,17] At the Oak Ridge facility, a 331 m long linear accelerator accelerates beam pulses of H- ions to almost 90% of the speed of light. These ions are stripped of their electrons upon entering a pulse accumulator ring that combines 1000 linac pulses into much larger pulses of protons. These proton pulses—shorter than a microsecond—are ejected from the ring at 60 Hz towards the neutron generating spallation target. At the SNS source this target consists of 20 tonnes of circulating mercury that can handle 2 MW of proton beam power on target. Cavitation erosion of the steel vessel containing the mercury was recognized as a problem at a late time in facility construction. It is caused by the tensile pressures that result from the response of the vessel to the transient high pressure (up to 40 MPa) pulses generated in the inertially confined mercury when it is heated over microsecond timescales by the proton pulse. Failure of a mercury vessel *outer* wall—while not a credited containment boundary—would require immediate change of the target which has consequences for the neutron science user program and cost (procurement and waste disposition). One solution under development at SNS is to introduce non-condensable gas bubbles into the bulk of the mercury that can absorb the pressure pulse and attenuate cavitation

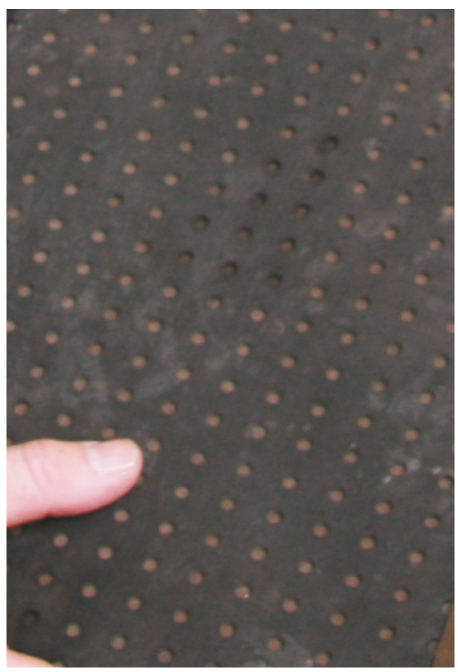

FIG. 8. (Color online) A piece of anechoic tiling from a WWII German U boat. The tiling was designed in response to the effectiveness of the Allied anti-submarine activities, which the Germans attributed to advances in Allied sonar, but which is likely to have been due to other factors (including the cracking of the Enigma Code). The far side of the tile is smooth, but the side visible in the picture was glued to the hull, trapping air in its circular pores. The technique is acoustically effective, though in early versions the tiles debonded from the hull under pressure cycling.

formation. In this way, it is envisaged that cavitation bubble activity on the vessel walls is low energy, and erosion there is reduced. Using the two-tube rig that was re-used for this demonstration, such sensors were developed and fitted to an SNS test facility to assess small gas bubble populations generated in the mercury flow.[1,31]

In addition to attenuating signals by absorption, bubbles also scatter sound, as demonstrated in the way they shorten the "organ pipe" as they rise [Fig. 5(c)]. Whilst such scattering can hinder communications and sonar in bubbly water,[32] it has many potentially useful applications. It is used to provide contrast agents[33] for diagnostic ultrasound (microscopic bubbles, injected into the bloodstream, highlight ultrasonic images) and has led to speculation as to how whales might exploit such scatter in feeding,[1,34] or how dolphins might mitigate against it when echolocating.[35,36] More experienced audiences can be led into discussions of the acoustical excitation of bubbles specifically in tubes, such as the ear canal during underwater hearing,[37,38] the blood vessel when ultrasonic contrast agents assist imaging[39,40] or if used for ultrasound-mediated drug and gene delivery,[41,42] and how all these relate to the dynamics of conical bubbles which can be made to collapse in pipes to generate transient temperatures of several thousand degrees.[43–45]

VI. CONCLUSIONS

The comparison of the acoustic absorptions of air bubbles in water, and water droplets in fog, build upon understanding of key features of acoustics (that sound generates oscillatory pressure and displacement fluctuations at a given location; and that acoustic absorption presents the conversion of mechanical energy ultimately into heat) to demonstrate a number of interesting phenomena. The demonstration is suitable for children, because they can leave it satisfied that they have understood something new. However it also contains sufficient complexity to give undergraduate- and Masters-level students questions to explore, and so learn through investigation.

The demonstration packs into a large car or small van and travels well. Items to be careful of, if traveling, are that if kept overnight in a cold car, condensation on contacts in the power amplifier should be avoided (we take the electronics into our overnight lodging to keep it warm); the neoprene membrane should be regularly checked for wear as it will eventually leak (after 3 years, in our case); and the dry ice should be provided by the host, since it is not safe to transport this in a vehicle unless extreme care is taken to avoid asphyxiation.

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[46]See supplementary material at http://dx.doi.org/10.1121/1.3676732 for two sound files and one movie file. Interested readers are also advised to look at http://www.isvr.soton.ac.uk/fdag/PIPE_DEMO/index.htm, which contains additional material, and to see Ref. 1 which can be downloaded from http://wwwnew.isvr.soton.ac.uk/staff/pubs/pubs90.htm. The movie file (bub1205.wmv) shows how effective is the mobile phone vibrator at making small bubbles, and in turn how effective they are at attenuating the sound. The movie starts by showing large bubbles injected into the water column by the needle (the bubbles are large because no voltage is applied to the mobile telephone vibrator attached to the needle). The oscilloscope screen shows strong acoustic pings picked up by the hydrophone—these large bubbles do not absorb sound well. Then the voltage to the vibrator is increased to 3 V, the bubbles are smaller, and the acoustic signal is more attenuated. Then the voltage to the vibrator is increased to 4.5 V. The same amount of gas is being injected in, but distributed amongst a greater number of smaller bubbles. The signal is strongly attenuated. After the voltage to the vibrator is turned off, it takes a long time for the hydrophone signal to return to its original level because the small bubbles take a long time to rise out of the water path between source (which is beneath the needle) and hydrophone. The sound file “water_wav.wav” contains the data record of Fig. 5(a), i.e., the unfiltered hydrophone record from just before bubbles are injected, until the signal begins to return as the bubbles clear. The bubble injection tone and rising note (as the cloud rises up the tube) are clearly audible. The sound file “fog_wav.wav” contains the equivalent data record from the microphone in the air-filled tube, from just before the fog is added until the time when the signal returns as the fog dissipates.