Bubble acoustics

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ABSTRACT

Gas bubbles are the most powerful acoustical sources and sensors that occur naturally in liquids. The potent interaction between bubbles and sound fields is exploited in applications as diverse as monitoring the transfer of greenhouses gases between atmosphere and ocean using the sounds of breaking ocean waves, to monitoring blood flow in the body by scattering ultrasound of bubbles injected into the patient. In the natural world, whales and dolphins go to extraordinary lengths of exploit this potent interaction, for example when trying to trap prey in the bubble nets they blow. Industry exploits this interaction in numerous ways, a new ultrasonic cleaning technology being used as an example.

Keywords Bubbles, cavitation, cleaning, ultrasound

1 INTRODUCTION: THE POWER OF ACOUSTIC BUBBLES

Figure 1(a) shows an image of the aftermath of a water drop impacting a body of water, the half-submerged lens clearly revealing the water jet that rises into the air as, below it, the crater shrinks in the water surface. However the famous ‘plink’ sound of dripping tap is not caused by either of those features: it is generated by the tiny bubble that was pinched off from the base of the closing crater. This illustrates how powerful an acoustical entity is a gas bubble in liquid. Each bubble behaves like an underwater bell, small ones producing plinks of high notes, and larger ones generating low notes (Minnaert, 1933).

When an ocean wave breaks, therefore, it generates many bubbles, each ‘singing’ its own note, and from the overall sound we can determine the number and size of bubbles containing trapped atmospheric gas, which can form bubble clouds in the upper ocean [Figure 1(b)] (Leighton and Walton, 1987). These bubbles are responsible for the transfer between atmosphere and ocean of many hundreds of millions of tonnes of atmospheric carbon each year. However to quantify this climatically-important carbon transfer, it is not sufficient simply to know how many bubbles are injected into the ocean by breaking waves. One must also know how many are left some time after the wave has broken, after some bubbles have risen to the surface, and others have dissolved. To do this, we project sound at the bubble clouds, and from the scatter we quantify how this undersea bubble population evolves, producing models of the shape and size of the undersea bubble clouds [Fig. 1(c)] (Leighton, 2004; Leighton *et al*., 2004). These models allow us to quantify the effect of bubbles on the transfer of carbon between atmosphere and ocean.

(a) **(b)** **(c)**

Figure 1. (a) The aftermath of a water drop impact on a body of water. (b) Undersea bubble clouds. (c) Frame shot of bubble clouds modelled after waves have broken in a region of ocean.

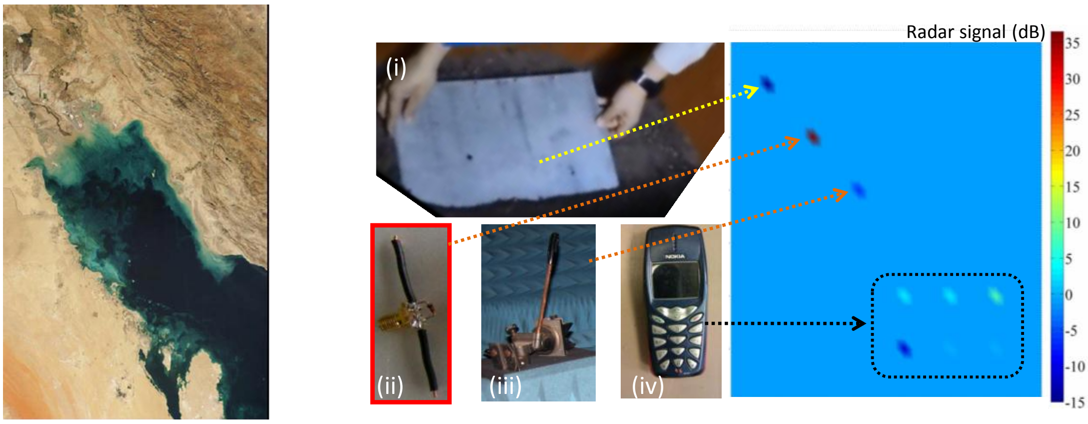
2 WHALES, DOLPHINS AND BUBBLE ACOUSTICS

Our ability to model the scattering of sound by undersea bubbles allowed us to postulate the mechanism by which humpback whales trap prey within spiral bubble nets. Although it had been known for decades that whales blow bubbles to do this, the reason why the prey do not escape the trap was not known. Our models [Fig. 2(a)] showed that the spiral bubble net traps the loud calls emitted by whales to produce an impassable 'wall of sound', whilst simultaneously creating a quiet zone in which the prey would congregate, this zone occurring in the model at the exact location where the rising whales feed [as photographed in Fig. 2(a)] (Leighton *et al*., 2007). However unlike humpback whales, dolphins use high frequency sonar to find prey, and the bubble nets they create [Fig. 2(c)] would confound their sonar. Rather than accept that such dolphins would 'blind' their most spectacular sensory apparatus when hunting, we set about proving that a previously unknown type of sonar processing (TWIPS) could detect prey in bubble nets (Leighton *et al*., 2010, 2011), and showed a variant of this to work with dolphin sonar calls (Leighton *et al*., 2012). Industry is now developing this to protect shipping in coastal regions such as the Persian Gulf, where clouds of bubbles and particles in the near-shore waters make mine detection difficult [Fig. 3(a)].

(a) (b) (c)

Figure 2. (a) Model (left) of acoustic rays based on a photographed spiral bubble net (photo by T. Voorheis of Gulf of Maine Production). (b) Image of a dolphin blowing bubbles to catch fish (Image courtesy of The Blue Planet. BBC).

Realizing that this new processing system could work with radiations other than just sonar, we used it to develop a radar system (TWIPR) where the scattering off circuitry from a bomb trigger was more than 1000 times (30 dB) more powerful than the scattering off other targets [Fig. 3(b)] (Leighton *et al*., 2013a). With the ability selectively to detect mobile phones as readily as bomb triggers, TWIPR can help finding buried targets of interest (bombs, people carrying phones buried by collapsed buildings or avalanches) where normal radar would not be able to identify the genuine target from other debris [typified in Fig 3(b) by (i) & (iii)].



(a) (b)

Figure 3. (a) Coastal clouds of bubbles and suspended sediment in an aerial image of Persian Gulf (image courtesy J. Descloitres, MODIS Land Rapid Response Team at NASA GSFC). (b) TWIPR Radar signal from (i) an aluminium plate, (ii) a circuit resembling components of a bomb trigger; (iii) a rusty bench clamp; (iv) mobile phones in various states.

3 COLD WATER CLEANING

Having established the power of bubbles to change the acoustic environment, we will consider one aspect of the power of bubbles to change their physical environment when sound is projected at them (Leighton, 2007).

Of particular interest were the changes that could be induced by the growth of surface waves (Maksimov and Leighton 2001, 2012; Leighton, 2004; Maksimov *et al*., 2008; Birkin *et al.,* 2011) on the bubble wall, which if controlled could greatly enhance the rates of chemical reactions (Birkin et al., 2001, 2002, 2004; Watson et al., 2003) and electrodeposition (Offin et al., 2007). However, the most important application we proposed was in the ability of such waves to generate 'cold water cleaning'.

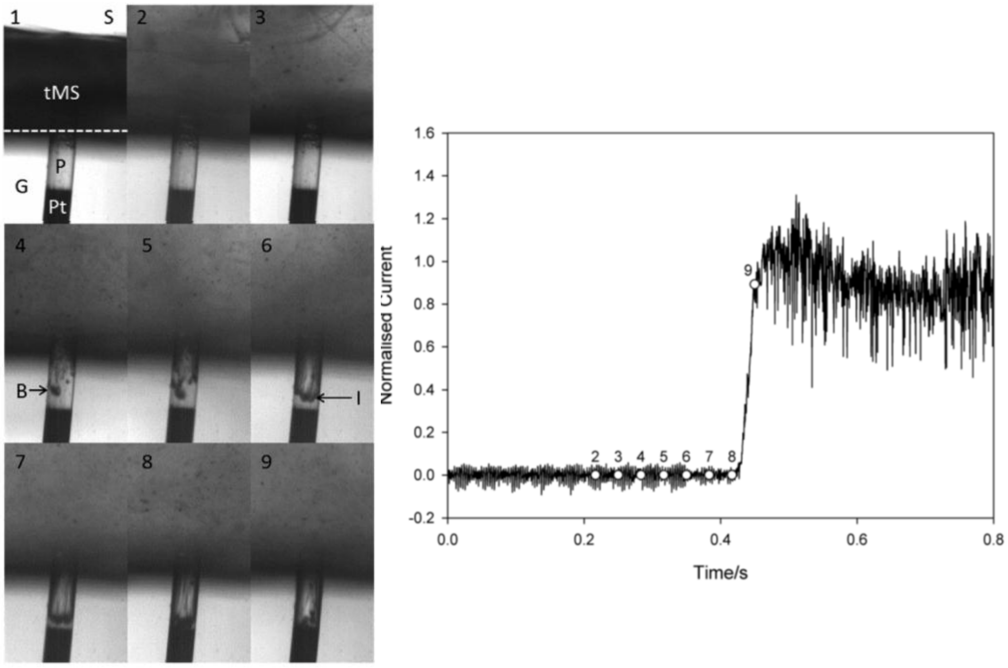
Traditional ultrasonic cleaning baths are limited (Leighton *et al*., 2013b) in that they cannot clean objects that are too large to fit in the bath, and cannot be taken to objects with complex geometries in order to ′clean in place′. Furthermore the object to be cleaned sits in a ′soup′ of contaminated liquid, and whilst cavitation fields can be set up under test conditions, immersion of the object to be cleaned can significantly degrade the bath′s performance by disrupting the sound field. An alternative technique, which does not use ultrasound is the commercial pressure-/power-washer, where high speed jets of water and cleaning agent are pumped onto a surface. Although these can ′clean in place′, they pump large volumes of water, and produce significant volumes of contaminated run-off and contaminated aerosol, both of which are hazards for secondary contamination of users and water supplies. The momentum of the water and pump requirements mean they are difficult to scale up. The challenge here was to produce a low volume flow technique for ultrasonic cleaning in place, benefits being that it operates with low flow rates (1-2 litres per minute), and there is no need to expend energy on heating the water (Leighton, 2011).

The proposition that cleaning could be achieved using low volumes of cold water, without additives, in a gentle flow, was an ambition for many years (Leighton, 2011; Leighton *et al*., 2013b). The challenges for cleaning are not simply related to today's use of too much water, too many additives, and too much energy to heat the water. An additional challenge is that, whilst it can be simple to clean flat surfaces, it can be more difficult to remove dirt from crevices, cracks and pores.

The solution was to use ultrasound to generate surface waves that cause the bubbles to act like tiny 'scrubbing machines', and furthermore to make the bubbles seek out crevices and cracks and clean within them. Figure 4(a) shows a sequence of selected frames illustrating the effect of ultrasonic cleaning in a glass block that contains a small cylindrical pore (Offin *et al*., 2014). The surface of the glass block and the pore are initially covered with a contaminant (tMS), which appears dark in the top half of frame (1) (its thickness within the small pore is not enough to make the image there opaque). At the base of the pore is an electrode, the current from which indicates whether the pore is clean or contaminated. At the start of insonification, the current is zero [frame (1), at time zero]. By 0.2 s [frame (2)] there has been substantial removal of the contaminant from the surface of the glass block, but the electrode current shows that the base of the pore is still dirty. By frame 4, however, the bubbles (one is labelled 'B') can be seen entering the pore, and the walls of the bubbles are rippled by surface waves that create shear in their vicinity, removing contaminant. The bubbles are driven by the acoustic forces towards the base of the pore, and by frame 6 only a small layer of contaminant remains in the pore (its upper surface labelled 'I'). When the bubbles reach the base of the pore [frame (9)] there is a rapid increase in the cleanliness of the electrode.

How do the acoustic forces cause the bubbles automatically to find the pore? When subjected to an external sound field, bubbles scatter that field, and that scattered field can influence the dynamics of nearby bubbles. When the bubble is near a flat solid surface (wall), the field it scatters is reflected off the wall, and returns to drive the bubble that caused it. From the bubble's point of view, the wall is acting like an acoustical mirror, and effectively the bubble acts as if there were a mirror image of itself on the other side of the wall, and equidistant from it. Two bubbles doing the same thing in a sound field attract (Leighton, 1994), and so the bubble is attracted to the wall, and stays on it rather than being flushed away. The bubble then wanders over the wall, cleaning as it goes, but if it sees a crevice, it effectively sees the multiple images that are produced when many mirrors are angled to one another. Therefore the bubble is attracted into the pore, and cleans it.

This example of the exploitation of bubbles and radiation forces has been incorporated into a device that will be launched by Ultrawave Ltd. in 2014.



(a) **(b)**

Figure 4. (a) A sequence of selected frames (filmed at 3000 frames per second, exposure time of each frame was 1/44000 s) showing the effect of ultrasonic cleaning in a glass block (whose upper surface is indicated by the dashed white line) that contains a cylindrical pore (125 mm diameter, ~350 mm depth, labelled 'P'). The glass (labelled 'G') is in a solution of 5 mM $K_3Fe(CN)_6$ and 0.1 M $Sr(NO_3)_2$ (labelled 'S') in an emulsion of water and F54 surfactant. The contaminant is labelled tMS. For details see Offin *et al*. (2014). (b) Plot showing the normalised current recorded at a platinum electrode [labelled 'Pt' in panel (a)] at the base of the pore as a function of time. The numbers above the time history correspond to the frame numbers in panel (a). The current is normalised to the average current recorded by the electrode in a clean pore under the same insonification conditions.

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