SPIRAL BUBBLE NETS OF HUMPBACK WHALES: AN ACOUSTIC MECHANISM

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Abstract: *Following the earlier proposal of an acoustic mechanism for the operation of the circular bubble nets of humpback whales, the authors have instigated studies of the spiral nets of humpback whales, which have been photographed in the wild. There is no information as to relative frequencies of occurrence of spiral as opposed to circular bubble nets, or nets of other geometries. However the spiral net offers several distinct advantages over the circular one in terms of the generation of an acoustic trap, containing some regions of bubble-free water which will be quiet when the whales insonifies the net with feeding calls. These advantages are demonstrated through simulation, and a physical scale model was used to demonstrate some of these features.*

Keywords: *Bubble net, humpback whale, waveguide, cetacean acoustics*

1. INTRODUCTION

In 2004, Leighton *et al.* [1] proposed that humpback whales use bubble nets as acoustics waveguides to create a sonic trap for prey. It had been known for decades that humpback whales, either singly or in groups, sometimes dive deep and then release bubbles to form the walls of a cylinder, the interior of which is relatively bubble-free. The prey are trapped within this cylinder, for reasons previously unknown, before the whales 'lunge feed' on them from below. When the whales form such nets, they emit very loud, 'trumpeting feeding calls'. Leighton *et al.* showed a how a suitable void fraction profile would cause the wall of the cylinder to act as a waveguide, creating a 'wall of sound' with a relatively quiet interior at the centre of the cylinder. They hypothesized that any prey which attempted to leave the trap would enter a region where the sound is subjectively loud and furthermore could excite swim bladder resonances [2-5]. In response, the prey would school, and be trapped ready for consumption (the bubble net turning the 'schooling' survival response into an anti-survival response).

The circular geometries modelled by Leighton *et al.* [1] were based on the frequent description in the literature of humpback bubble nets as 'circular', or as bubble 'rings' [6-15]. Since then however the authors had brought to their attention (by Dr. Simon Richards of QinetiQ) the existence of photographs showing the development of a spiral form of bubble nets by humpback whales (Fig. 1). This paper outlines the possible acoustical implications of spiral nets.

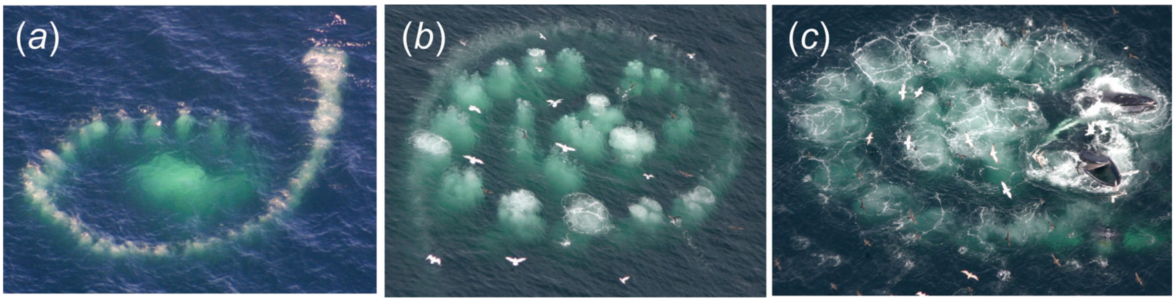


Fig. 1: Three images illustrating the formation (a)-(c) of a spiral bubble net, with lunge-feeding occurring in frame (c). Note the presence of opportunistic birds. (Photographs by Tim Voorheis / www.gulfofmaineproductions.com. Photographs were taken in compliance with United States Federal regulations for aerial marine mammal observation).

2. THE SPIRAL NET HYPOTHESIS

The authors hypothesize that spiral bubble nets may hold distinct advantages over circular ones [16]. In the circular bubble net of Leighton *et al.* [1], the propagating rays which form the 'wall of sound' are confined within bubbly water. As will be shown below, refraction can trap rays within a spiral bubble layer in a similar way [16]. However in both cases the rays trapped by refraction propagate through bubbly water, where the attenuation is greater than it would be for bubble-free water. It is therefore advantageous in forming a 'wall of sound' that the spiral bubble nets contain a second, complementary path, where the containment of the rays works through reflection, and crucially, the propagation occurs through bubble-free water where the attenuation is less. Furthermore the open end of the spiral forms a more robust entry point for the sound, and does not require shallow angles of the sort modelled by Leighton *et al.* [1] in order to create a wall of sound with a quiet interior. The trap is therefore much more tolerant to the positioning of the whale. There are yet further advantages to the spiral bubble net, compared to the circular one, detailed below.

The circular net requires closure of the circle in order to create a quiet bubble-free region. Of course the inner end of the spiral could close up upon itself, creating in effect a circular bubble net within a spiral one, with a quiet bubble-free region in the centre in which prey are trapped. However spiral nets do not need such accuracy in their construction: they will still work even if there is no complete closure of the bubble layer surrounding a bubble-free centre; and they will still work even if the centre is not bubble-free. This is because the spiral geometry generates a new region, free of bubbles and sound, within the inside edge of the bubble-free arms of the spiral. The ever-closing spiral wall means that, as they progress into the spiral, the reflected rays meet the outer edge of the bubble-free arm of the spiral with ever-decreasing grazing angles, such that the inner edge of the bubble-free arms remains quieter.

Whilst both the bubble-free and bubbly paths in the spiral individually contribute to the wall of sound, the interactions between them create a synergistic effect: there will be ray paths which propagate at times in the bubble layer, and then leave it to enter the bubble-free layer, of the spiral; and reflections at interfaces between bubbly- and bubble-free water will be only partial.

Fig. 2(a) shows the effect of just one ray as it enters the bubble-free arm of the spiral (all modelling in this paper is restricted by the limitations of ray representation, as discussed earlier [1]). When it first meets the outer edge of the bubble-free arm (at the point labelled A, here with a grazing angle of 34º), the subsequent propagation is represented by two rays: a refracted ray in the bubbly arm, and a ray which is reflected into the bubble-free arm. The refracted ray propagates in the bubbly waveguide. As it approaches the edge of the bubbly water in principle it may of course be internally refracted back into the bubbly water. Alternatively a given ray may intersect the edge of the bubbly waveguide, which in the model results in two rays propagating onwards: one is reflected back into the waveguide, whilst another is refracted into the bubble-free water (either within the spiral, or outside of it). Propagation within the bubbly waveguide is attenuated much more than propagation in the bubble-free arm. Because of the absence of attenuation in Figure 2(a), and because of the ability for rays to multiply at interfaces, there is of course no information in the figure with respect to acoustic intensity.

The ray which at A reflected into the bubble-free arm of the spiral, propagates through it until it next meets the bubbly water at B, with a reduced grazing angle (here, 29º). Again two rays are shown propagating away from B, a refracted ray (which recharges the attenuated sound field in the bubbly water), and a reflected ray which continues through the bubble-free water towards C. Further reflections at C, D etc. occur with reduced grazing angle, each one recharging the field in the bubbly water. The number of reflections is artificially truncated in the calculation at F.

The ever-reducing grazing angle will keep the inner edge of the bubbly net quiet, and the attenuation in the bubble cloud, and loss of energy from the ray in the bubble-free water each time it reflects, serve to reduce the sound field towards the centre of the spiral. In this way, quiet regions are generated. These are not just at the centre of the net, as with the circular net, but also along the inner edge of the bubble-free arm. Prey here will be in bubble-free, quiet water, but trapped within the spiral 'maze': in 2D, few positions will have an exit visible along the line of sight, and in real 3D nets the locations of the predators must be taken into account. Whilst Fig. 2(a) showed the results (without attenuation) of the launching of a single ray into the spiral, Fig. 2(b) shows a ray plot for the launching of a beam. As before, the plot lacks attenuation and requires the generation of both a refracted ray and a reflected one at interfaces, such that intensity information is incomplete. Note that the only rays with large grazing angles in the bubble-free arm have first propagated through the bubbly layer and suffered losses when refracting through the interface at least twice, and hence will be heavily attenuated.

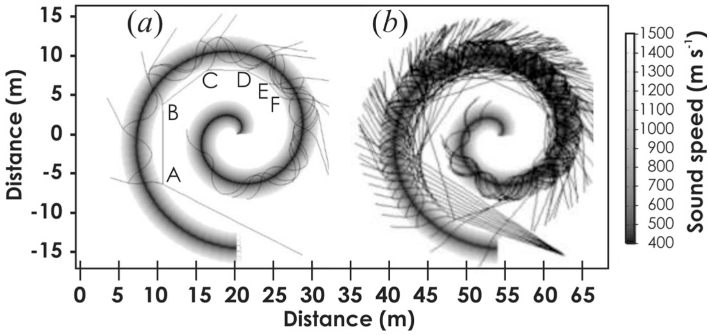


Fig. 2: Plan view of 2D spiral bubble net. (a) A single ray is launched. It reflects off the outer wall of the bubble-free arm of the spiral, the grazing angle decreasing each time (34º at A; 29 º at B; 23º at C; 19º at D; 16º at E; 13º at F). At each reflection, not only does a reflected ray propagate further into the bubble-free arm, but a refracted ray propagates into the bubbly-arm of the spiral. Attenuation is not included. (b) A beam of rays is launched into the spiral. The spiral generates clear regions which are both bubble-free and quiet (see [15] for details).

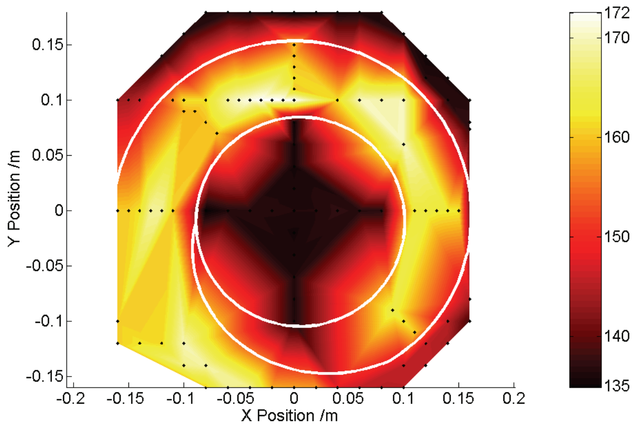
There are clearly simplifications in Fig. 2, some of which were discussed in [1] and [15], including 3D features, the low-frequency limitations of ray-tracing, and the effects of the departure in the actual wall of Fig. 1 from idealised smooth wall curvature of Fig. 2. The surface will appear most rough for the highest frequencies [15], which we take as 4 kHz [1]. For acoustic fields in bubble-free water, this gives a wavelength of 0.375 m, so that for test values of the mean height of the surface undulations of 0.1 m and 1 m, the wall will appear smooth for grazing angles less than about 37º and 4º respectively, with commensurately larger angles for lower frequencies. The angles compare well with the sequence of angles recorded in the caption to Fig. 2. For further discussion see [15].

Why some nets should be spiral is not clear. It may be a pragmatic or incidental response to practical limitations. Conceivably however the whales could be exploiting the different acoustical properties of circular and spiral nets. These could confer possible advantages to the spiral configuration through the following features. (*i*) A wall of sound can be generated using acoustic paths which propagate in bubble-free water (Fig. 2) and hence suffer less attenuation than seen for acoustic paths in bubbly water (to which circular nets are restricted). (*ii*) Propagation in the bubble-free arm 'recharges' the heavily attenuated field in the bubbly waveguide as both progress into the spiral, which serves not only to reinforce the wall, but also to attenuate the sound in the bubble-free arm to facilitate the generation of quiet regions in the centre of the net. (*iii*) The spiral net contains more scattering interfaces between 'bubble-free' and bubbly water, such that whilst a ray which leaves the circular net is lost from the net, a ray which refracts out of a region of bubbly water in the spiral net can remain trapped within the spiral system. Specifically, when a ray leaves the circular bubble net of Leighton *et al.* [1] it is lost to the 'wall of sound'; but except for rays crossing the outermost interface of the spiral bubble net, rays crossing boundaries in the spiral net remain contained within it. (*iv*) A spiral form which contains a closed inner ring of bubbles surrounding a bubble-free centre gives additional acoustic protection to the quiet zone at the centre of the net. High-angle rays need only cross two walls to penetrate the centre of the circular bubble net and degrade its quietness; in contrast, they must cross many such interfaces in the spiral net, reflecting at each boundary and attenuating across the width of several bubbly arms. (*v*) Spiral nets need not be generated to such exacting standards as to contain a closed inner ring of bubbles surrounding a bubble-free centre. They generate quiet, bubble-free zones at locations against the inner edge of the bubble-free arm.

The geometry of Fig. 2(b) shows how the whale could speculatively obtain feedback on the performance of the spiral net, since the efficiency of the "wall of sound" could be diagnosed through monitoring the outbound sound as it leaves the spiral.

3. DISCUSSION

Fig. 3 shows the measured sound field generated in a very simple 1:100 scale demonstration bubble net (generated by submersing expanded polystyrene in water because it is not simple to produce a 1:100 scale model of a bubble population where the mode bubble radius can just a few tends of microns in diameter). For details see Leighton *et al.* [15].



Colour scale: rms sound pressure level (dB re 1 μPa) at each measurement location, time-averaged over the entire 2 ms window from the start of one pulse to the start of the next (pulses having ~8 μs free-field duration of a 375 kHz basic frequency sinusoid), so that all the reflections within the spiral were included in the calculation.

Fig. 3: Measured acoustic field in horizontal plane in demonstration spiral bubble net of expanded polystyrene (1:100 scale, so that the Blacknor Technology sound source projected a 375 kHz pulse into the open end of the spiral). The white line shows plan view position of spiral. Data only exists for the discrete measurement points shown as black dots: between these the colour indicates an interpolation and so, whilst visually appealing, cannot include the zero-pressure at the spiral wall. See [15] for details.

To what extent the humpback whales make use of these acoustical properties is not known, as it is difficult to obtain objective measurements of the sound field, and an assessment of whether whales exploit these features would require a survey which correlated behaviour with acoustics. The geometries of net used have not been comprehensively surveyed, let alone the relative occurrence of spiral, circular and any other net geometry. However without simultaneous acoustic information, behavioural observations and reliable bubble data (there may be volumes of microscopic bubbles which, although they have a pronounced acoustic effect, are not visible in the photographs, but which can persist for many minutes in the water column), and in sufficient quantity, it is impossible to be certain as to the extent, if any, humpback whales are exploiting these. It may be that the formation of spirals nets is simply the by-product of some behaviour designed to achieve another purpose, such as efficient motion during the formation of the net, just as the shape of natural spirals whose response to pressure perturbations is key to their function (e.g. the cochlea, the nautilus shell) has been attributed to expedient (if the perhaps mundane) explanations such as efficient packing. However the remarkable effect of the spiral on fields propagating along it (such as the ever-decreasing grazing angle which will, if the spiral is sufficiently long, eventually generate wall-hugging surface waves; the robustness to the particulars of the entry; and the possibility of feedback from back-propagating fields) are suggestive of possibilities that should be explored.

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