Modeling Backscatter of Marine Mammal Bio-mimetic Sonar Signals from Bubble Clouds

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Abstract - **Bubbles are powerful and complex sound scatterers in water because of the impedance mismatch at each water-air/gas interface. Bubbles are formed by natural processes that include rainfall, gas emission from the sea bed, boat wakes, living or decomposing organisms, and wave breaking- the latter being the dominant cause of bubble entrainment in the surf zone. Despite the complications of sound propagation in bubble-populated water, some species of cetaceans have been observed to hunt efficiently in shallow coastal waters and in biologically active rivers where bubbles persist. In contrast, the performance of man-made sonar systems has always been greatly handicapped by this phenomenon and improvement is necessary.**

How cetaceans manage to overcome the problem of echolocating through bubbles clouds is still largely unknown. However, if we can gain a more complete understanding of the ways in which bubbles respond to echolocation signals transmitted by cetaceans, this might provide insight into the strategies they use for detecting prey under such conditions, or, indeed, how they manipulate the 'bubble screen' effect to catch fish. New insights could then contribute to the development of improved, bio-mimetic sonar systems for use in difficult environments such as the littoral zone.

This paper presents a model describing the backscatter of marine mammal bio-mimetic sonar signals from bubble clouds. Echolocation signals from a dolphin and a porpoise were modeled, and we simulated the backscatter response of single bubbles from a discretized bubble population distribution when driven by each type of echolocation click. Responses from individual bubbles with various radii were then used to find the total bubble cloud backscatter response.

This paper explores the backscatter from bubble clouds using two types of bio-mimetic echolocation pulses that have different signal characteristics.

I. INTRODUCTION

Acoustics plays an important and necessary part in our daily lives. We have evolved to use sound as a primary sense and speech as the main (although by no means exclusive) communication channel for social interaction among individuals. This ability is not limited to the human species as animals, too, have evolved a complex set of vocal tools to assist in their social interactions. In addition, some species have evolved a remarkably complex neuro-audio system to replace (or augment) vision in environments in which optical vision is severely challenged. Most bats and some species of marine mammals are able to use sound to aid navigation, and to detect objects in extreme and harsh environments where vision is obscured; and, no doubt, terrestrial equivalents can be referred to. For marine mammals in particular, the use of vision is extremely limited in the underwater environment, especially in deep waters where there is little illumination, or in coastal or benthic waters with high turbidity from sediments and phytoplankton. To overcome this problem, some species of marine mammals use sound in the form of echolocation signals to augment or replace their sense of sight underwater.

Bubbles are efficient scatterers of sound in water because of the impedance mismatch at the liquid to gas interface. Bubbles are formed by natural processes that include rainfall, gas emission from the sea bed, boat wakes, living or decomposing organisms, and wave breaking: the latter being the dominant cause of bubble entrainment in the surf zone. Despite the complications of sound propagation in bubble populated water, some species of cetaceans have been observed to hunt efficiently in shallow coastal waters and in biologically active rivers where bubbles persist.

Advancements in technology have assisted humans to partially recreate the underwater echolocation ability of marine mammals. These man-made (SONAR) systems can out-perform marine mammal echolocation in some respects but they also have limitations which make them inferior under the most difficult circumstances. One of the major problems faced by man-made sonar systems is the effect of poor signal to noise performance caused by loss of signal strength between transmission and reception of echoes. This problem has the greatest impact in shallow waters and especially in the surf zone where the void fraction is high.

How cetaceans manage to overcome the problem is still largely unknown, but if we can gain insights on how echolocation signals propagate and scatter from clouds of micro-bubbles, it would help us better understand how to design bio-mimetic systems that work effectively in these environments.

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II. BACKGROUND

A. Bubble Dynamics and Equation of Motion

In the study of bubble dynamics, one observes the behavior of gaseous cavities in a body of liquid when subjected to an acoustic disturbance. A time-varying, generally sinusoidal pressure source is superimposed on the ambient pressure environment, causing any cavities present (bubbles of gas in the liquid medium) of an appropriate size to be in set into a state of motion in which both expansion and contraction phases are present. This behavior is defined as *bubble oscillation*.

One of the important factors that determine the kind of response from a bubble is the relationship between the frequency of the external oscillating pressure field and the natural frequency of the bubble. A bubble will oscillate most when driven by a signal whose frequency matches its natural frequency. The other factor is the amplitude of the signal, which, together with the driving frequency, determines whether a bubble will undergo linear or non-linear oscillations.

A gas bubble in a liquid acts like an oscillator. Minnaert (1993) was the first to calculate the natural frequency of a spherical gas bubble in a liquid [1]. The Minnaert resonance frequency is defined as:

$$w_0 = \frac{1}{a_0}\sqrt{\frac{3\kappa p_{i,e}}{\rho}} \tag{1}$$

where w_0 is the resonance frequency, a_0 is the resonance bubble radius, κ is the polytropic exponent of gas, $p_{i,e}$ is the equilibrium pressure inside bubble and ρ is the density of water.

Another form of the equation that takes surface tension into consideration is:

$$w_0 = \frac{1}{a_0}\sqrt{\frac{3\kappa p_{i,e}}{\rho} - \frac{2\sigma}{p_0 a_0}} \tag{2}$$

where σ is the surface tension and p_0 is the atmospheric pressure.

A bubble's natural frequency is a function of its radius as shown in (1) and (2). Bubbles found commonly in the ocean are dominated by those with radii ranging from 10 to 100 μm. Resonance oscillation can occur when the frequency of the driving pulse matches the natural (resonance) frequency of the bubble. A bubble driven at its resonance frequency will have a response which is primarily a function of damping by the medium in which it is suspended. Given that viscous damping is small in most practical circumstances, the bubble will undergo large oscillations exceeding its critical size. This results in a highly non-linear scattering response.

For simplification, bubbles are often assumed to be spherical and always remain spherical. The equations of motion for the liquid are derived from conservation equations for mass and momentum and from equations of state for the liquid. These equations give the relationship between changes in enthalpy, density and pressure in the liquid. By combining these basic equations and making some simplification assumptions, the partial differential equations describing the motion of the liquid are reduced to an ordinary differential equation describing the bubble radius as a function of time. The equation of motion for a bubble will be discussed in the following section.

Keller and Miksis (1980) [2] produced a radial equation based on the assumption of a constant speed of sound in the liquid. This equation is suitable for large amplitude forced oscillations and incorporates the effects of acoustic radiation by the bubble. It also uses the approximation of a linear polytropic index. Prosperetti (1984) [3] modified this equation to incorporate a more exact formulation for the internal pressure. This modified Herring-Keller equation is given as:

$$\begin{aligned} &a\ddot{a}\left(1-\frac{\dot{a}}{c}\right)+\frac{3}{2}\dot{a}^2\left(1-\frac{1}{3}\frac{\dot{a}}{c}\right) \\ &=\left(1+\frac{\dot{a}}{c}\right)\frac{1}{\rho}\left(p_L - p_0 - p_i\left(t+\frac{a}{c}\right)\right)+\frac{a}{\rho c}\frac{\delta p_L(t)}{\delta t} \end{aligned} \tag{3}$$

where a is the instantaneous bubble radius, $\dot{a}$ is the instantaneous bubble wall velocity, $\ddot{a}$ is the instantaneous bubble wall acceleration, c is the speed of sound in water, p_L is the liquid pressure at the bubble wall, p_i is the driving pressure.

The liquid pressure at the bubble wall, p_L is given as:

$$p_L = \left(p_0 + \frac{2\sigma}{a}\right)\left(\frac{a}{a_e}\right)^{3\kappa} - \frac{2\sigma}{a} - \frac{4\eta_L \dot{a}}{a} \tag{4}$$

where η_L is the sheer viscosity of the liquid.

Assuming that the liquid is incompressible, the pressure at a distance r from the bubble center is given by:

$$p_s = \frac{a}{r}\left(\frac{1}{2}\rho\dot{a}^2 + p_L - p_\infty\right) - \rho\frac{\dot{a}^2 a^4}{2r^4} \tag{5}$$

B. Marine Mammal Echolocation

Dolphins produce sound that can be classified into two broad categories. The first type is frequency-modulated signals of moderately long duration lasting between one-tenth of a second to several seconds that are referred to as whistles. They are suggested to be used for con-specific communications [4]. The second type is characterized by broadband impulses in the ultrasonic frequency range with very short durations (in the order of microseconds) and high sound intensity which is referred to as echolocation clicks. They are mainly used for navigation and detection.

Echolocation is the process of projecting acoustic signals and sensing the surrounding environment from the echoes. Acoustic energy propagates most efficiently in water compared to other forms of energy. As such, it is no surprise that many marine mammals have evolved to use sound to augment or

replace their sense of sight for navigation and detection underwater.

Echolocation signals can be further classified into two general categories. The first category is signals of dolphins capable of whistling and the second category is signals of dolphins that do not whistle. The echolocation signals from the second category compared to those from the first category are of a longer duration, narrower bandwidth and lower intensity [5].

Echolocation signals from marine mammals that whistle vary slightly among species but they generally have some common features that distinguish them from the other category. In general, these echolocation clicks typically have less than 3 to 5 cycles, with the first cycle reaching its maximum amplitude (oligocyclic waveform). They have broad bandwidth and high sound intensity. Echolocation signals emitted by two Atlantic bottlenose dolphins (*Tursiops truncatus*) were made by Au *et al.* (1974) during a target detection experiment in open waters of Kaneohe Bay, Oahu, Hawaii [6]. The signals were observed to have peak frequencies ranging from 120 to 130 kHz and an average peak-to-peak click level on the order of 220 dB re 1 µPa. Another set of signals recorded from the same species was describe by Au (1980) in which signals were observed to have peak frequencies ranging from 110 to 130 kHz and an average peak-to-peak click level of 228 dB re 1 µPa. These clicks have a 3 dB bandwidth from 30 to 60 kHz and have durations of approximately between 50 to 80 µs [7].

Most species of porpoises fall into the category of non-whistling marine mammals. The echolocation waveform envelope increases in amplitude from the first few cycles and decays exponentially (polycyclic waveform). They generally have a narrower frequency range and longer duration than echolocation signals from whistling marine mammals. One reason why porpoises use long duration, narrow bandwidth signals is because of their size. They emit signals that have much lower energy than other larger odontocetes and hence they compensate for this energy difference by emitting longer and narrow-band signals [5]. Echolocation signals of finless porpoise (*Neophocaena phocaenoides*) measured in open waters were reported by Li *et al.* (2005). The peak frequency typically ranged from 87 to 145 kHz with an average of 125 ± 6.92 kHz and the 3dB bandwidth range from 15 to 25 kHz with an average of 20 ± 4.24 kHz. The duration of these signals ranged from 30 to 122 µs with an average of 68 ± 14.12 µs [8]. Peak to peak sound pressure levels measured by Li *et al.* (2006) were estimated to range from 163.7 to 185.6 dB re 1 µPa [9].

III. MODEL AND RESULTS

A. Simulated Marine Mammal Echolocation Clicks

A close approximation of a simulated porpoise chirp can be defined by applying a Hanning window to a 125 kHz sine wave with 9 cycles (corresponding to a duration of 72 µs). The amplitude of the simulated porpoise chirp is chosen to be 316 Pa (170 dB re 1 µPa), which corresponds to the average sound pressure level of echolocation chirps emitted by finless porpoises measured in the sea [9]. The waveform and power spectrum of the simulated porpoise chirp is shown in Fig. 1.

Au (1993) suggested that a typical sonar click resembles an exponentially damped sinusoidal wave with a duration between 40 and 70 µs and with 4 to 10 positive excursions [10]. He used a mathematical expression consisting of a Gabor function and a Gaussian curve to describe a simulated dolphin click as in (6),

$$s(t) = A\begin{bmatrix}\cos(2\pi f_0 t+\phi)\\ or\\ \sin(2\pi f_0 t+\phi)\end{bmatrix} e^{-\pi^2\frac{(t-\tau_0)^2}{\Delta\tau^2}} \qquad (6)$$

where A is the relative amplitude, f_0 is the centre frequency, t_0 is the centroid of the signal, $\Delta\tau$ is the rms duration of the signal and ϕ is the phase shift.

The simulated dolphin click used here has an amplitude of 10 kPa, a center frequency of 125 kHz and a rms duration of 30 µs. The waveform and power spectrum of the simulated dolphin click is show in Fig. 2.

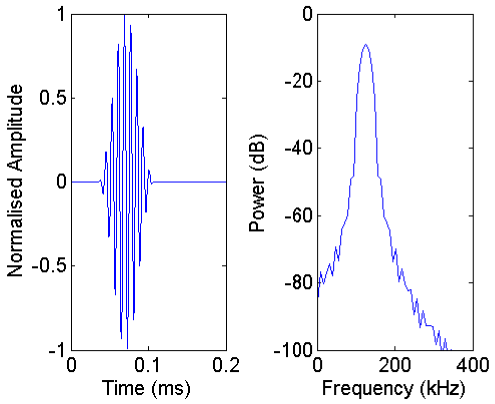

Figure 1. Waveform and power spectrum of a simulated porpoise chirp.

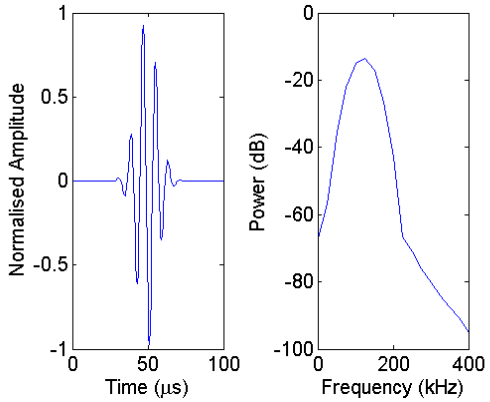

Figure 2. Waveform and power spectrum of a simulated dolphin click.

B. Bubble Cloud

The bubble cloud is assumed to be spherical dispersion with a 1 m radius consisting of a poly-dispersed distribution of microbubbles. The bubble population distribution used here is modeled after the work by Meers *et al.* (2000) [11], in which he described the population distribution beneath a breaking wave as a function of bubble radius:

$$n_b = 6\times10^6 e^{-0.02(R_0)} \quad (7)$$

where n_b is the number of bubbles in 1 cubic meter of water per micrometer increment and R_0 is the bubble radius.

In formulating the model, it was not computationally feasible to consider a continuous range of bubble size. Leighton *et al.* (2007) [12] described a bubble cloud comprising bubbles within 5 logarithmically spaced radius bins with centre radii: 10, 50, 100, 500, 1000 and 5000 μm. Using (7), they found the bubble cloud gave a void fraction in the order of 10^{-6}. The bubble population distribution used in their model is reproduced in Table 1. The same distribution was used in the model described here.

TABLE 1
BUBBLE POPULATION DISTRIBUTION

Bubble radius (μm)	Size bin radius limits (μm)	Number of bubbles in size bin per cubic meter of seawater
10	$10^{0.75} \le R_0 \le 10^{1.25}$	3.5×10^7
50	$10^{1.25} \le R_0 \le 10^{1.75}$	3.3×10^6
100	$10^{1.75} \le R_0 \le 10^{2.25}$	3.0×10^4
500	$10^{2.25} \le R_0 \le 10^{2.75}$	3.1×10^2
1000	$10^{2.75} \le R_0 \le 10^{3.25}$	3×10^0
5000	$10^{3.25} \le R_0 \le 10^{3.75}$	0

C. Single Bubble Backscatter in Response to Marine Mammal Echolocation

The backscatter pressure amplitude response from a single bubble was obtained by solving for the bubble radius and velocity using (3) and substituting into (5). The result was then compensated for the propagation delay and spreading loss measured by the receiver.

The center frequency of the simulated porpoise chirp was 125 kHz, which corresponded to the resonance of a bubble with a radius of approximately 24 μm. With sufficiently high driving pressure, bubbles with a radius close to the resonance size should give a highly non-linear backscatter response. However, the simulated porpoise chirps have considerably low source levels which would only give a linear backscatter response for the range of bubble radii considered. The waveform and power spectrum of backscatter from two bubbles with radii of 50 and 500 μm, when driven by a simulated porpoise chirp measured 1m from the bubble are shown in Figs. 3 to 6. Backscatter from the 50 μm bubble shows an under-damped response which appears mostly linear. Very weak harmonic scattering is observed in the power spectrum of the backscatter from the 10 μm bubble. Backscatter from the 500 μm bubble resembles that of the original driving pulse. The larger bubble scatters more energy because of the larger scattering cross section.

The simulated dolphin click also has a center frequency of 125 kHz. However it has a much shorter time duration and higher amplitude compared to the simulated porpoise chirp. The increase in amplitude results in nonlinear scattering in bubbles near the resonance bubble radius. The waveform and spectrum of backscatter from a bubble with radius 50 and 500 μm, when driven by the simulated dolphin click at 1 m from the bubble are shown in Figs. 7 to 10. The 50 μm bubble scatters nonlinearly and harmonic peaks can clearly be observed in the power spectrum shown in Fig. 8. The waveform plot in Fig. 7 also shows that that the bubble scatter is asymmetrical about the zero pressure axis. The 500 μm bubble which has a radius much greater than the resonance bubble radius scatters linearly.

D. Bubble Cloud Backscatter in Response to Marine Mammal Echolocation

Calculating the total back-scatter pressure response from a bubble cluster was no trivial task especially if multiple scattering between bubbles was considered. However the computational process could be simplified by assuming a low bubble void faction. This allows bubble responses to be uncoupled. The bubble population distribution described earlier gives a void fraction in the order of 10^{-6}, which fulfills this criterion. The return signal from the whole bubble cloud can be formed as a summation of convolutions, with one convolution representing the return from the bubbles in the cloud within a size bin, where the delay is proportional to each bubble position in the cloud with respect to the driving sound source, and the weight proportional to spreading loss. While the bubble responses can be non-linear, superposition still holds for the scattered signals. This significantly helps to reduce the computational load.

The waveform and power spectrum of the bubble cloud backscatter when driven by a simulated porpoise chirp measured at 1 m from the center of the bubble cloud are given in Fig. 11 and 12 respectively. Although responses from individual bubbles in the cloud can add up constructively and destructively due to the phase differences cause by individual bubble positions, the overall response from the bubble cloud still appears to be dominated by the driving (fundamental) frequency. This observation can be accounted for because of the low sound pressure amplitude of the driving pulse which produces linear scattering in individual bubble response.

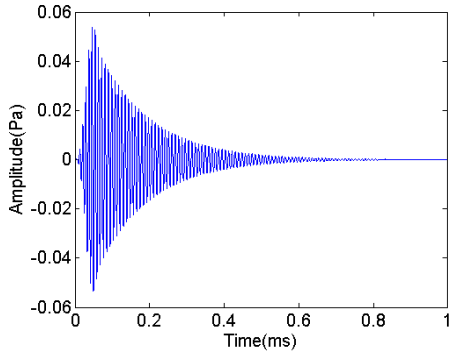

Figure 3. Waveform of a 50 μm bubble driven by a simulated porpoise chirp.

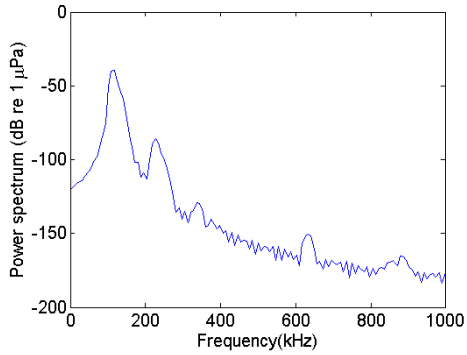

Figure 4. Power spectrum of a 10 μm bubble driven by a simulated porpoise chirp.

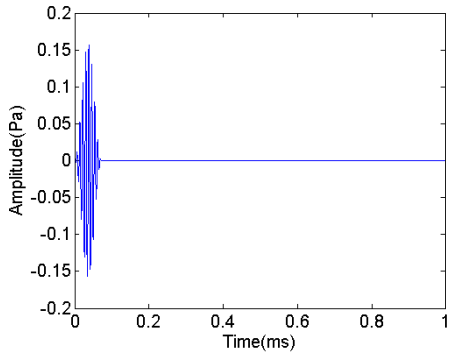

Figure 5. Waveform of a 500 μm bubble driven by a simulated porpoise chirp.

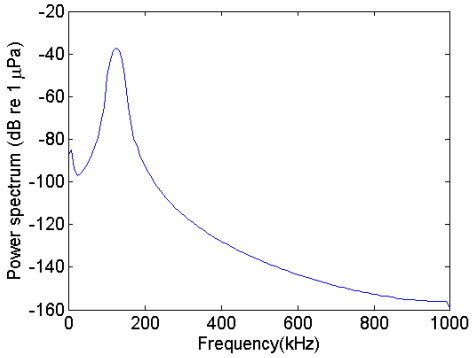

Figure 6. Power spectrum of a 500 μm bubble driven by a simulated porpoise chirp.

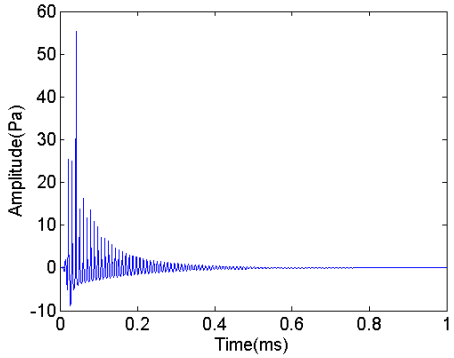

Figure7. Waveform of a 50 μm bubble driven by a simulated dolphin click.

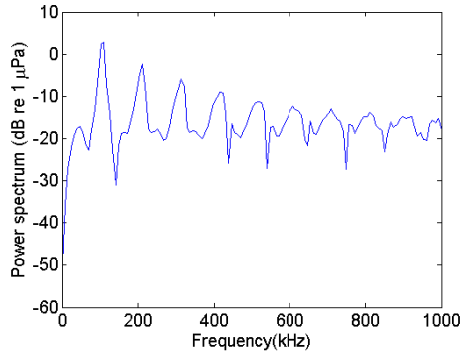

Figure 8. Power spectrum of 50 μm bubble driven by a simulated dolphin click.

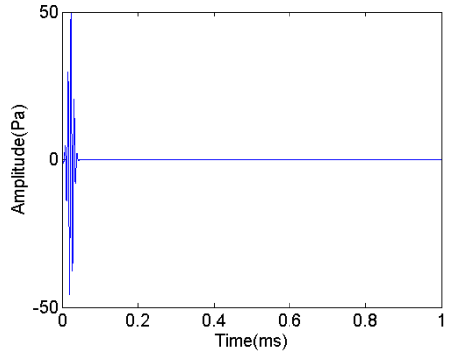

Figure 9. Waveform of a 500 μm bubble driven by a simulated dolphin click.

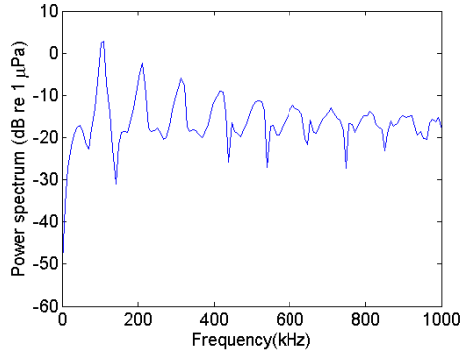

Figure 10. Power spectrum of 500 μm bubble driven by a simulated dolphin click.

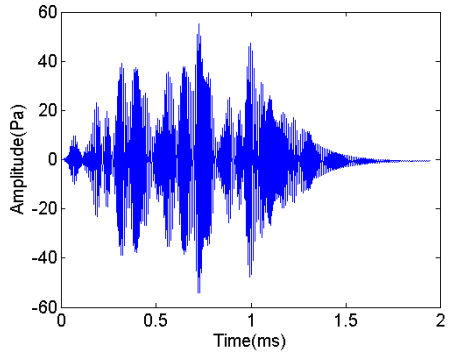

Figure 11. Waveform of bubble cloud backscatter when driven by a simulated porpoise chirp.

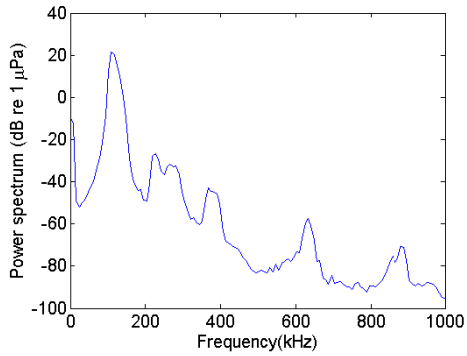

Figure 12. Power spectrum of bubble cloud backscatter when driven by a simulated porpoise chirp.

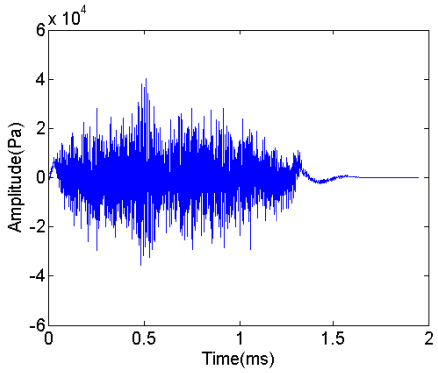

Figure 13. Waveform of bubble cloud backscatter when driven by a simulated dolphin click.

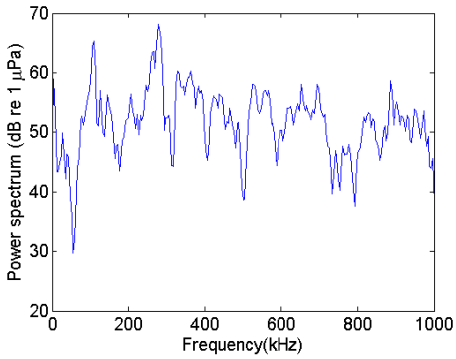

Figure 14. . Power spectrum of bubble cloud backscatter when driven by a simulated echolocation click.

The waveform and power spectrum of the bubble cloud backscatter when driven by a simulated dolphin click measured at 1 m from the center of the bubble cloud are given in Fig. 13 and 14 respectively. The major differences here compared to the backscatter response from a simulated porpoise chirp are the backscatter amplitude and frequency response. The peak amplitude of the backscatter from a simulated dolphin click is on the order of 10^4. This difference is because of the high amplitude of the driving pulse and also because of the high amplitude non-linear scatter from bubbles that have radius close to the resonance size. The power spectrum in Fig. 14 shows 2 significant peaks at approximately the driving (fundamental) frequency and at twice the fundamental frequency (harmonic). The harmonic peak has a larger amplitude then the fundamental. This presence of harmonics is a clear indication of non-linear scattering from the bubble cloud scatter here.

IV. CONCLUSION AND FUTURE WORK

A model for finding backscatter of marine mammal bio-mimetic sonar signals from a bubble cloud has been presented. Simulation results have shown that the backscatter from a bubble cloud driven by simulated porpoise chirps produces a linear response. This is because of the low driving pressure amplitude produce by this category of non-whistling marine mammal. On the other hand, simulation results have shown that the bubble cloud backscatter driven by simulated dolphin clicks give a non-linear response.

Leighton *et al.* suggested the possibility of marine mammals using pulse inversion techniques for contrast enhancement in the surf zone [13]. They proposed the Twin Inverted Pulse Sonar (TWIPS) technique, which is a signal processing algorithm applied to the backscatter from a pair of closely-spaced, high amplitude transmit pulse of opposite polarity. It was suggested that the algorithm could help to either enhance linear scattering from targets while suppressing non-linear scattering from bubbles, or vice versa.

The results presented in this paper show that dolphins do produce echolocation pulses that generates non-linear scattering from a bubble cloud. Moreover, the frequency of their echolocation clicks corresponds to a resonance bubble size that dominates the distribution found in the surf zone environment where they have been observed to hunt effectively. It would be interesting to explore the application of TWIPS to dolphin echolocation clicks and provide a measure of its effectiveness in target detection. This could provide insights into the development of improved bio-mimetic sonar systems in difficult environments such as the littoral zone.

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