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THE POSSIBILITY AND EXPLOITATION OF NONLINEAR EFFECTS IN THE NEAR-SURFACE OCEANIC BUBBLE LAYER

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As models of acoustic propagation within the near-surface oceanic bubble layer have developed over the last four decades, the assumptions inherent within them have been refined. The earliest models assumed that only resonant bubbles contributed. Later models incorporated the effects of non-resonant bubbles, but assumed that all the bubbles would be undertaking linear steady-state and monochromatic pulsations. Without such assumptions it is not, for example, possible to exploit many convenient mathematical techniques, such as complex representation of propagating wave. Nevertheless the elimination of these assumptions reveals certain features, such as the time- and amplitude-dependence of bubble-mediated attenuation, which might be exploited in enhancing underwater communications or active sonar in bubbly waters.

1. INTRODUCTION

Acoustic propagation through bubbly water has been modelled only with the introduction of the assumption of bubble linearity, or linearisation of the bubble dynamics, at an early stage. Probably the most notable example is the pioneering work of Commander and Prosperetti [1], which has been cited over 100 times since publication and used in many more acoustic investigations. If this linearisation is not done, not only do the formulations become inherently more complicated, but several useful mathematical techniques are not valid. These include complex representation of oscillations, small amplitude expansions, Green's function, Fourier transforms, superposition and addition of solutions. A nonlinear approach was recently proposed by Leighton *et al.* [2], which shows how attenuations and sound speeds can be calculated in inhomogeneous time-dependent bubble clouds subjected to time-dependent insonification (e.g. pulses of arbitrary time history). It was shown how the method can be applied to populations of bubbles which are undergoing linear or nonlinear pulsation [2,3]; which are in free field or reverberant conditions [4]; or to bubbles which are constrained by structures [5,6], or surrounded by media other than pure water (such as tissue, sediment, or interacting bubbles) [7-10]. The characteristics of propagation in bubbly water have been known for decades, although new applications (such as in the operation of the bubble nets of humpback whales [11] and other marine creatures [3,12]) are still being discovered. The possibility of predicting and interpreting nonlinear effects, however, which the new model provides, opens up exciting possibilities, and these will be the topic of this paper.

The theory [2] for non-linear acoustic propagation through bubble clouds has been used to:

- Invert measured acoustic propagation characteristics in the surf zone to determine the bubble size distribution [2,13], and compare the results with inversions undertaken using the linear technique of Commander and McDonald [14], which exploits the linear propagation of Commander and Prosperetti [1];
- Predict the amplitude dependency of attenuation in oceanic bubble clouds [2];
- Predict the pulse-length dependency of attenuation in oceanic bubble clouds [2];
- Compare the errors which might accrue through neglect of the nonlinearity of bubble pulsations in high amplitude fields, with those which occur through neglect of bubble-bubble interaction [2].
- Investigate techniques by which sonar echoes from solid objects (such as mines) could be enhanced in comparison to those from bubbles in the vicinity of the mine, and *vice versa* [3,12]

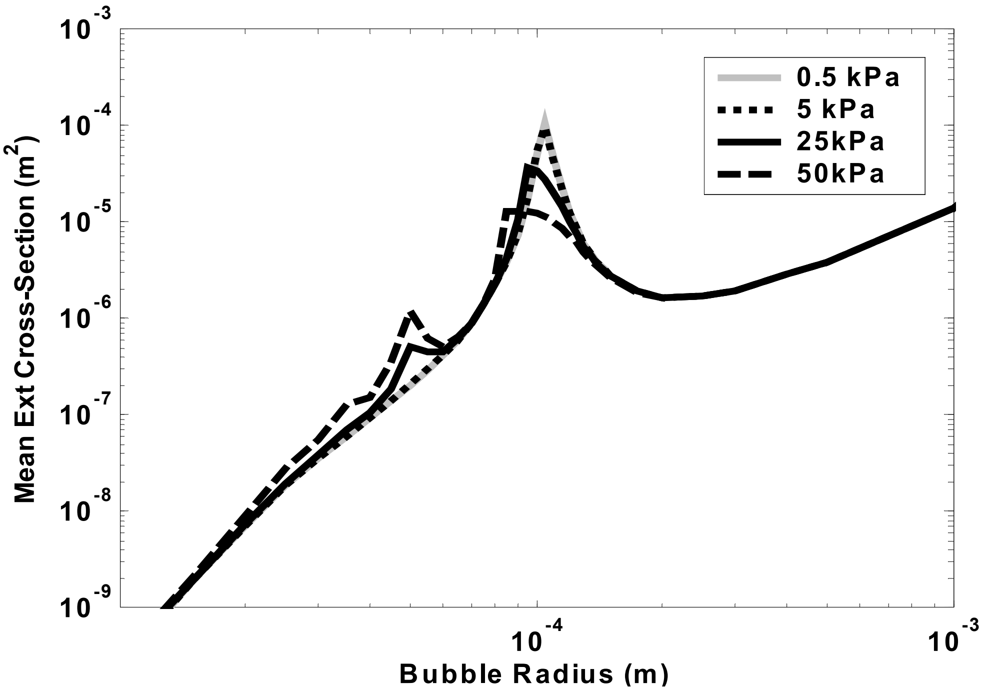
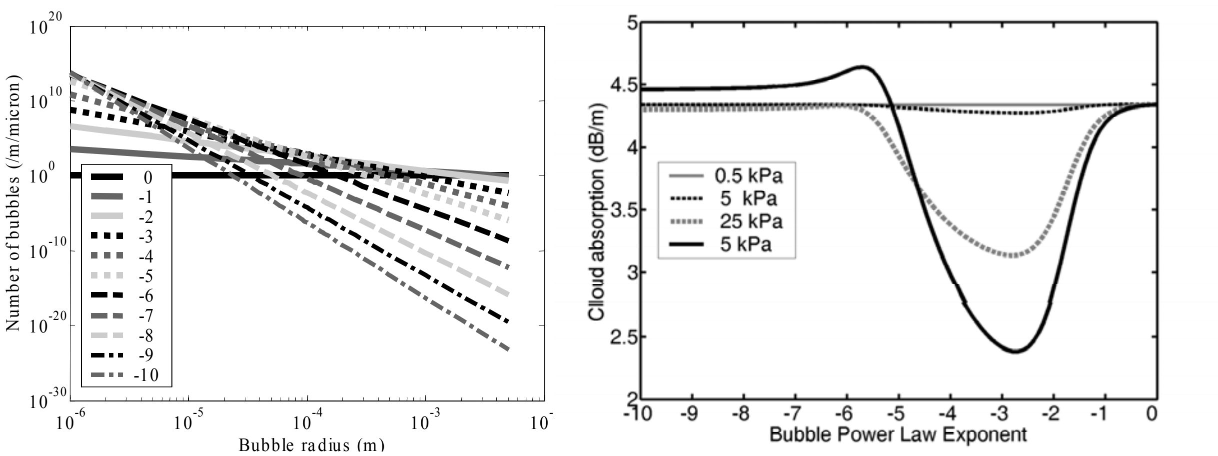


Fig.1: Acoustic extinction cross-section for a single bubble, as a function of the radius of that bubble, for insonification by a 1 ms duration pulse of 33 kHz centre frequency and 0-peak pulse amplitudes in the range 0.5-50 kPa. The cross-section calculated by the formulation of Leighton et al. [2] varies over time, and the figure plots its mean value. Although the 0.5 kPa and 5 kPa lines differ (particularly close to the fundamental resonance), they are barely distinguishable on this scale. Because the cross-section is not defined during ring-down [2], losses in that period cannot of course be included in this figure.

One obvious scenario where insonification amplitudes sufficiently high to excite nonlinearities might be used is when the void fraction is high, generating severe attenuation. Leighton *et al.* [2] showed that, in such circumstances, the errors which accrue from neglect of the nonlinearity, during propagation which is of sufficiently high amplitude to excite it, can be much greater than the errors which result from neglect of bubble-bubble interactions.

However the ability to incorporate nonlinear bubble dynamics into models of acoustic propagation is not restricted to their use in systems where the void fraction is so high as to make high amplitude insonification an unavoidable necessity. With any bubble cloud, nonlinear pulsations can be generated and the results exploited as an additional diagnostic tool. The scatter from the bubbles might be enhanced or suppressed, relative to those from other structures, by exploiting the nonlinearity [3,12].



(a) *(b)*

Fig. 2: (a) Various bubble populations, expressed in $n(R_0)$(bubbles/m^3 per micron bin width in radius) scaled such that the attenuation at low power levels in (b) will be the same for all bubble distributions (b) Cloud absorption for various power law bubble distributions $n(R_0) \propto (R_0)^x$ (for x=0,-1,-2…-10) where the number of bubbles is scaled as described in (a), for insonification as in caption for Figure 1. Note that the constant offset at high power for -7 to -10 power laws might be due to rounding errors for the bubble response of 1 micron bubble which is amplified by 10^{14} number of bubbles. The difference is not noticeable on the extinction cross-section plot.

2. IMPLICATIONS OF THEORY

A not unexpected nonlinear effect in the steady-state would be a decrease in attenuation as the amplitude of the driving pulse increases (equivalent to a decrease in the acoustic absorption cross-section, with commensurate decrease in the acoustic scattering cross-section). This might be expected if the attenuation (and scatter) scale with the amplitude of pulsation of the bubble. That is to say, we are assuming for the moment that, in the bubble population in question, it is the fundamental of the pulsation resonance (rather than, say, a geometrical affect) which is causing attenuation and scatter (for discussion of such circumstances, see Leighton [12]). As the driving amplitude increases, the amplitude of the bubble pulsation cannot increase proportionately: in the simplest illustration, the displacement on compression cannot of course be greater than the bubble radius. One source of this nonlinearity is the bubble stiffness [12]. Hence if the driving amplitude increases, the bubble response cannot increase proportionately, and we see a decrease in the ratio of the powers scattered and absorbed by the bubble, to the intensity of the incident driving field (the acoustic scatter and absorption cross-sections, respectively). This can be illustrated in Figure 1, where the peak corresponding to the bubble pulsation fundamental resonance decreases with increasing driving amplitude.

However the picture is more complicated than the simple correspondence between fundamental resonance pulsation and attenuation/scatter assumed above. It is true that if the bubble population were to be dominated by resonance bubbles, the attenuation would decrease with driving amplitude. However with the decrease of the fundamental resonance peak in the acoustic extinction cross-section, there are corresponding increases in the cross-section corresponding to bubbles having radii of about 50, 35 and 25 microns, corresponding to bubbles whose pulsation resonances would be multiples of the insonifying frequency (66, 99, 132 kHz respectively). If the bubble population were to be biased such that there were sufficient numbers of bubbles responding at the second harmonic, the growth in the peak would mean that attenuation could in fact increase with driving amplitude. Figure 2a illustrates a range of bubble population distributions characterised by a power law, and Figure 2b plots the predicted attenuation as the amplitude of the driving field increases. Whilst the general trend is that attenuation decreases with driving amplitude (as described above), it is clear that for bubble populations with power law exponents of ~5.5, increasing the driving amplitude can first decrease and then (at even higher drive amplitudes) increase the attenuation. Therefore by measuring the attenuation at various driving powers, it would for example be possible for a single-frequency source to gain information on the bubble size distribution over an octave or more.

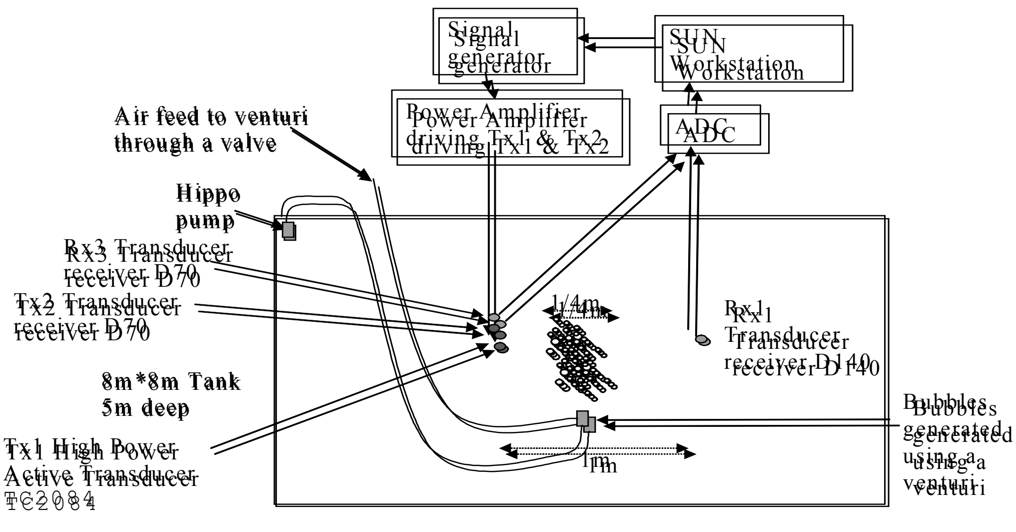


Fig.3: Schematic of experiment.

3. TESTING

Figure 3 shows the experimental setup. Bubbles were generated in the large tank using a venturi system with the water flow supplied by an underwater Hippo pump and the air was sucked down through a hose by the pressure drop created by the venturi. The airflow was regulated by the use of a valve to adjust the bubble distribution and the void fraction. The bubble population was determined using a transmitter receiver pair (Tx2-Rx1) to measure the attenuation over 1 m for several frequencies in the 10-100kHz range at low power levels. A high power directional transmitter (Tx1) transmits sonar signals through the bubble cloud, which were then detected by an omni-directional receiver (Rx1) 1 m away and the backscattered signals from the cloud are detected by omni-directional receiver (Rx3). The transmit signals were generated by a signal generated (output +/- 2V peak) which was fed into a Krohn-Hite power amplifier (x100 output +/- 200V peak). The receive signal was filtered and converted by an analogue digital converter (ADC) and then recorded in the SUN workstation, which contained the analysis software.

Features, which complicate such an experiment, include the variability of the bubble cloud. If, for a constant bubble size distribution, the bubble numbers fluctuate by a factor ε, the dB/m attenuation in the measurement scales accordingly. If the attenuation of a plane wave of intensity I with distance z is $dI/I = -\Omega_C dz$, then the attenuation (dB) due to the bubble cloud is given by $\alpha_C = -10\log_{10}(I_C / I_0) = -10\log_{10}\left(e^{-\Omega_C z}\right) = (10\log_{10} e)\Omega_C z_C$, where I_0 & I_C are the intensities before and after the cloud respectively and z_C is the distance across the cloud. If the cloud cross-section fluctuates from Ω_{C1} to $\Omega_{C2} = \varepsilon\Omega_{C1}$, the resulting attenuation increases from $\alpha_{C1} = (10\log_{10} e)\Omega_{C1} z$ to $\alpha_{C2} = (10\log_{10} e)\Omega_{C2} z = \varepsilon\alpha_{C1}$. Figure 4 shows some preliminary measurements for attenuation measured through the cloud, for groups of three pulses of 0.75 ms duration and spaced 15 ms apart. The three consecutive pulses in each group have amplitudes 0.5, 5 & 50 kPa, measured at the cloud. The interpulse time is a compromise: it must be sufficient to allow reverberation and natural bubble oscillations from the preceding pulse to decay, but short enough so that the three pulses interrogate a nominally identical bubble population. Each 0.5 s the insonification is repeated. Figure 4 shows that fluctuations in the cloud cause the attenuation to vary between 13 and 33 dB. The data in figure 4 should not be taken to imply a measured amplitude-dependent effect: the results are preliminary tests of the experimental protocol only.

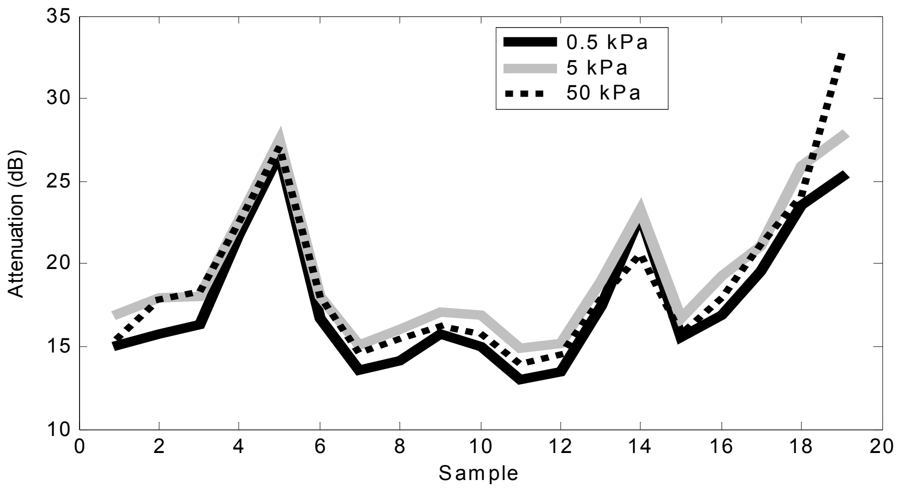


Fig.4: Bubble cloud attenuation for each group of 3 different peak acoustic pressure amplitudes (as stated in legend, as measured in bubble-free water at location where cloud centre will be).

In such a test, calibration is critical, before, after and during experimentation. Heating of the source, and bubble attachment to transducers etc., are just two sources of systematic drift in the calibration. Similarly, the no-bubble calibration should be done both in still water, and with the venture pump active but no air injected, so that the effect of such flow (and any sediment it carries) can be ascertained. Diffraction and refraction around the bubble cloud must be considered. Since the bubble population changes with depth [2], it must be measured along the relevant propagation path.

It is often the case that the importance of such artefacts decreases as the entity to become measured becomes larger. Here however that entity is the attenuation, and as this increases, the path length over which the bubbles behave nonlinearly (and so give rise to the effects of interest) also decreases. Backscatter measurements might therefore provide a simpler route for verification of the theory.

4. ACKNOWLEDGEMENTS

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