Time-dependent scattering from bubble clouds: Implications for the use of acoustic pulses

J W L Clarke[1], T G Leighton[1], G J Heald [2], H A Dumbrell [2],

[1]Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK, *jwlc@isvr.soton.ac.uk*

[2]Defence Evaluation Research Agency, Bincleaves, Newtons Road, Weymouth, Dorset DT4 8UR, UK

Summary A theoretical model has been developed to investigate the time-dependent acoustic scatter and extinction cross-section of gas bubbles in fresh water. Particular emphasis has been placed on the 'ring-up' times, or time taken to reach steady state oscillation, of gas bubbles in fresh water. The model has also been extended to determine the acoustic cross-sections of bubble clouds of varying population distributions (assuming no bubble-bubble interactions). The results have shown that the ring-up time of a bubble is dependent on its closeness to resonance and the driving pressure amplitude. Investigation of various bubble populations has shown that the ring-up time of the resonant bubbles may be masked by the presence of large off-resonant bubbles, and that high amplitude sound fields enhance this effect. The implications of these findings for the use of acoustic pulses to detect objects within bubble clouds, are explored by comparing the predictions of the model with experiment.

INTRODUCTION

The resonant and off-resonant scattering characteristics of bubbles are well defined and are utilised in a large number of applications, including measurement of oceanic bubble populations and research into upper ocean dynamics (1). However, it is these same characteristics that make acoustic detection of non-bubble targets in areas with dense bubble populations (such as the surf-zone) difficult.

One possible solution to this problem utilises the bubble 'ring-up' time, or the time taken for a bubble to reach steady state oscillation, at resonance. Theory suggests that, owing to inertial effects, this ring-up time will be finite and that, prior to reaching steady state oscillation, the acoustic scattering will be greatly reduced. A pulse length dependent reduction in scattering, attributed to 'ring-up' time, was first detected by Akulichev (2) in 1985. However, two more recent studies have failed to measure any such reduction in scattering (3,4). This paper outlines theoretical and experimental work used to ascertain possible reason why Suiter (3) and Pace *et al.* (4) did not detect any reduction in scattering.

THEORY

A theoretical model of the time-dependent scattering and extinction cross-sections of a single bubble has been developed to investigate the response prior to steady-state oscillation (5). The model has then been extended to cover clouds of non-interacting bubbles. The model exploits the Herring-Keller bubble equation (6,7). Whilst the prediction of the scattering cross-section use the full non-linear calculations, those of the extinction cross-section require the theory to be linearised with respect to the losses. This employs the formulae of Prosperetti (8). The resulting extinction cross-sections are therefore an approximation only and care must be taken when considering higher driving sound pressure levels (when bubble motion is highly non-linear). This paper compares with experiment the predictions for the acoustic scatter cross-section, which will be more robust for the higher driving amplitudes.

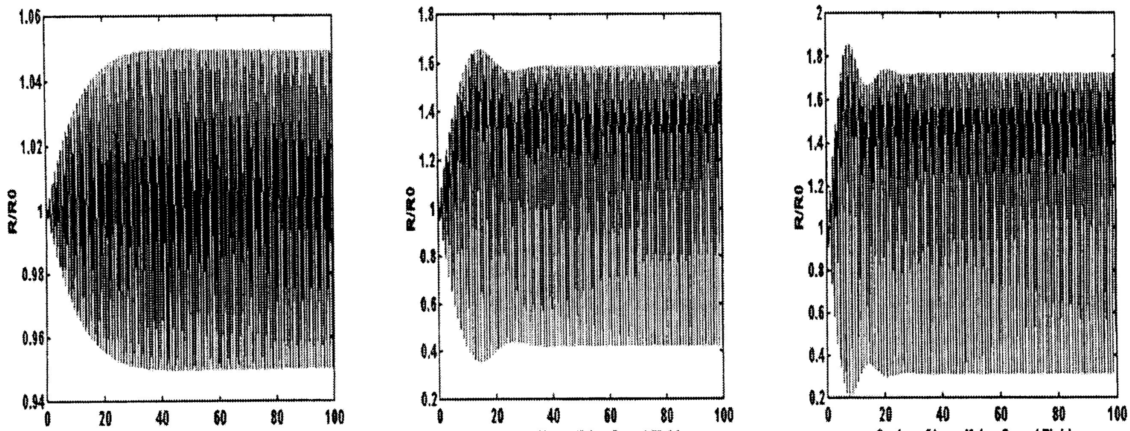

FIGURE 1 Bubble wall radius R normalised by the equilibrium radius R_0 for a resonant bubble (R_0=14.5μm) in a 200 kHz sound field of a) 500 Pa, b) 10000 Pa and c) 20000 Pa peak to peak sound pressure level.

The bubble wall response and the scattering cross-section have been calculated for a peak-to-peak sound pressure level of 500 Pa, 10000 Pa and 20000 Pa. The results are shown in figures 1 and 2 respectively. It can be clearly seen that despite the increase in amplitude of bubble wall oscillation (figure 1) the scattering cross-section decreases with increasing sound pressure level (figure 2). This is because the definition of the scattering cross-section normalises the power scattered by the bubble to the intensity of the incident plane wave. The reduction in the time taken to reach steady-state as the driving amplitude increases (figure 2) also indicates that the likelihood of detecting 'ring-up' effects increases as the driving pressure is reduced.

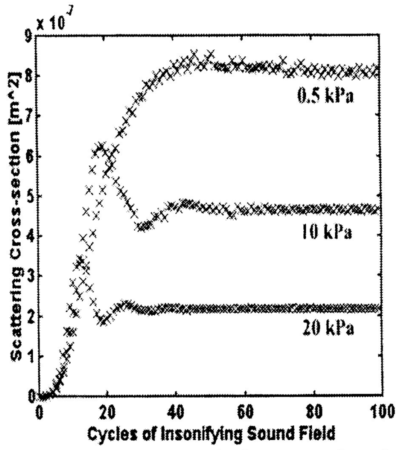

FIGURE 2 Predictions of the scattering cross-section for driving amplitudes of 0.5, 10 and 20 kPa for a resonant bubble in a 200 kHz sound field.

The above analysis can be expanded to give a first-order estimation of the time-dependent extinction cross-section of a bubble cloud that is valid for void fractions less

0.02%. Thus by calculating the scattering cross-sectional area of a single bubble of varying radii and compiling the results, the effective response of a bubble layer with a given population distribution can be calculated (5).

EXPERIMENT

In order to measure the response of an oceanic-type bubble cloud (9) under laboratory conditions, an electrolysis type bubble cloud generator was developed. The oxygen producing electrode (anode) was mounted above the cathode with a set of filters placed between to remove hydrogen bubbles from the cloud. By varying the current the population density can be controlled.

The bubble cloud generator was placed at the bottom of an 8 m x 8 m x 5 m deep freshwater test tank. A high frequency, monostatic transmit/receive array was deployed to measure the response of the cloud to various length signals. The amplitude of the incident wave at the cloud was also measured using a separate hydrophone.

A preliminary example of the experimentally determined backscatter from the bubble cloud is shown in figure 3a. This has been processed to give an estimate of the scattering efficiency of the cloud by summing the total response and dividing by the incident intensity. The resulting plot is shown in figure 3b. Care must be taken interpreting these results due to the finite dimension of the bubble cloud (~ 0.5 m diameter).

Consider the case when the length of the pulse train is shorter than the cloud dimension. If the cloud were comprised of linear oscillators with minimal ring-up time, the scattered energy would scale approximately with the ratio of the length of the pulse train to the cloud dimension. This is because as the pulse train length increases, more scatterers are being insonified at any given time. However the rate at which the scattered energy increases with increasing pulse length is not as great once the pulse train length exceeds the cloud dimension. In reality, the response will in addition include the 'ring-up' and 'ring-down' times of the bubbles that make up the cloud, and thus the response will be non-linear.

CONCLUSIONS

The theory has shown that the time to reach steady-state oscillation for a resonant bubble is dependent on sound pressure level. Prior to steady state, the scattering cross-section is smaller and could potentially allow enhanced acoustic penetration of bubbly media.

Initial experimental measurements of backscatter from an artificially generated bubble cloud have shown trends in the pulse-length dependence of scatter, which qualitatively agrees with the expectations. Such trends suggest that an enhancement of acoustic penetration of bubble clouds is in principle possible, although further work is required to determine whether it would be practicable under field conditions. Further development of the model will allow quantitative comparisons, by incorporating both the ring-up times of individual bubbles, and the cloud dimension.

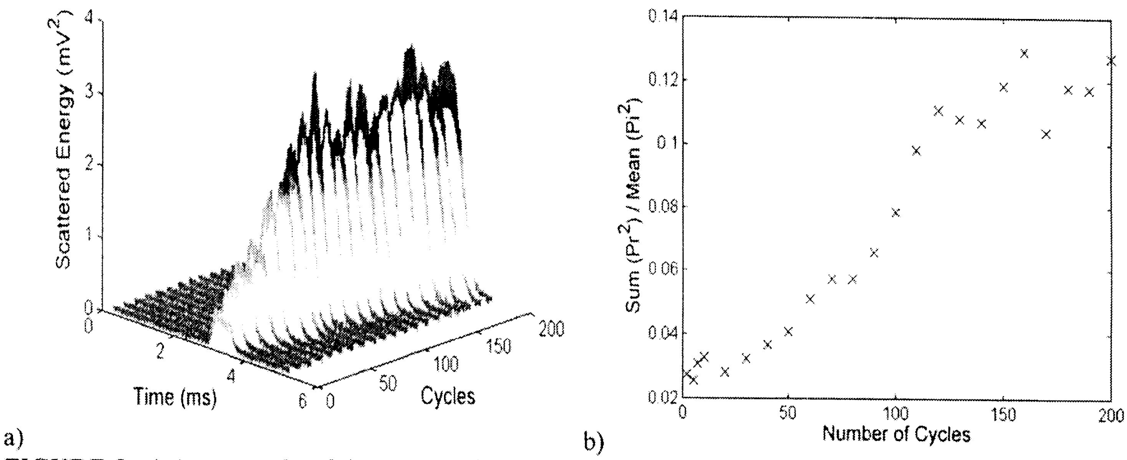

FIGURE 3. a) An example of the measured response of a bubble cloud to a 200 kHz, ~370 Pa peak to peak sound field averaged over 100 pings. b) The response has been processed to estimate scattering efficiency where Pr is the radiated acoustic pressure from the bubble cloud and Pi is the incident driving sound pressure level.

ACKNOWLEDGMENTS

The authors wish to acknowledge funding from the Defence Evaluation Research Agency (contract no. SSDW1/647) and are very grateful to Mr R Evans for invaluable scientific and technical input.

REFERENCES

1 Thorpe, S A, "Bubble clouds and the dynamics of the upper ocean", *Quart. J. Royal Met. Soc.* **118** (503), 1-22, (1992)
2 Akulichev, V A, Bulanov, V A, Klenin, S A, "Acoustic sensing of gas bubbles in the ocean medium", *Sov. Phys. Acoust.* **32**, 177-180, (1986)
3 Suiter, H R, "Pulse length effects on the transmissivity of bubbly water", *J. Acoust. Soc. Am.* **91**, 1383-1387, (1992)
4 Pace, N G, Cowley, A, Campbell, A M, "Short pulse acoustic excitation of microbubbles", *J. Acoust. Soc. Am.* **102** (3), 1474-1479, (1997)
5 Clarke, J W L, Leighton, T G, "A Method for Estimating Time-dependent Acoustic Cross-sections of Bubbles and Bubble Clouds Prior to the Steady State", *J. Acoust. Soc. Am.* Submitted December1998
6 Herring, C, "Theory of the pulsations of the gas bubble produced by an underwater explosion", OSRD, Rep. No. 236, (1941)
7 Keller, J B, Miksis, M, "Bubble oscillations of large amplitude", *J. Acoust. Soc. Am.* **68**, 628-633, (1980)
8 Prosperetti, A. "Thermal effects and damping mechanisms in the forced radial oscillations of gas bubbles in liquids". *J. Acoust. Soc. Am.* **61**, 17-27 (1977).
9 Phelps, A D, Leighton, T G, "Oceanic bubble population measurements using a buoy deployed combination frequency technique", *IEEE J. Oc. Eng.* **23** (4), 400-410 (1998)