Proceedings of the Fourth European Conference on Underwater Acoustics
Edited by A. Alippi and G. B. Cannelli
Rome, 1998

MEASUREMENTS OF THE OCEANIC BUBBLE POPULATION USING PROPAGATION CHARACTERISTICS AND COMBINATION FREQUENCY TECHNIQUES

T.G. Leighton, A.D. Phelps and M.D. Simpson

Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK

Acoustic measurements of the oceanic bubble population are presented. The paper describes two deployments: the first uses a combination-frequency system to determine the bubble population in a small volume (of order 1 ml), and the second additionally measures propagation characteristics determined from a two hydrophone array. This dispersive attenuation data can be used to infer the bubble population using finite element inversion techniques.

1. INTRODUCTION

The use of acoustical techniques are especially potent in bubble measurement [1], as there is a large backscattering of incident sound from the bubble wall. Additionally, when driven by a sound wave whose wavelength is much larger than the bubble radius, the bubble can pulsate as a single degree of freedom oscillator. The resonant frequency of these pulsations can be readily used to calculate the bubble radius.

A free-floating buoy was constructed to acoustically measure the oceanic bubble population, and was deployed from the back of a 30 foot research vessel in two separate sea trials. For the first deployment a single acoustic technique was employed to measure the bubble population, termed a *combination frequency* technique. For the second deployment, the buoy was radically redesigned to make it less invasive with respect to the sea surface action, and a *finite element inversion* technique was added to the buoy. In the second deployment, it was envisaged that the results from the two measurement procedures could be compared to allow quantitative measures of the relative accuracy and applicability of each, and also yield preliminary information on the evolution of the bubble cloud with depth.

The first technique uses a combination frequency excitation method, where the bubble population is simultaneously insonified with two sound fields. The first is a fixed high frequency (set here at 1 MHz) beam called the imaging signal ω_i, which scatters approximately geometrically from the bubble wall. The second is a much lower frequency signal, the pump signal ω_p, which is intended to drive the bubbles into resonant pulsation.

This frequency was varied between 17 and 200 kHz at ten discrete frequency values for the first deployment (which correspond to bubble radii between 192 and 15 μm) and between 28 and 200 kHz for the second deployment (113 to 15 μm). When the pump signal coincides with, or is close to, a bubble resonance, the scattered imaging signal is amplitude modulated as it scatters from a target whose area is varying in time. This generates signals at $\omega_i \pm \omega_p$. The benefits of using this technique are detailed elsewhere [2,3].

The second technique examines the dispersive transmission loss of a plane acoustic wave as it passes through the bubble cloud at 15 discrete frequencies [4]. The measured frequency dependent attenuation, $\alpha(f)$, can be related to the radially variant unknown bubble distribution $\Psi(a)$ through:

$$\alpha(f) = \int_{a_{min}}^{a_{max}} \sigma_e(f,a)\Psi(a)da \qquad (1)$$

where $\sigma_e(f,a)$ is the extinction cross-section of a bubble of radius a and frequency f, whilst a_{min} is the smallest radius in the measured population, and a_{max} the largest. To solve this equation for $\Psi(a)$, it is necessary to approximate the integral by expanding the unknown bubble distribution function into a finite sum of point estimates of the population at discrete radii values multiplied by appropriate linear B splines [4]. Having thus discretised the integral into a certain number of point measurements, equation (1) can be re-written, and a generalised matrix which relates the measured bubble mediated attenuation to the population number can be calculated. The successful calculation of the unknown bubble distribution relies on the accurate inversion of this matrix. However, the matrix contains significant terms off the leading diagonal. These are caused by the increase in a bubble's extinction cross section at frequencies much higher than its resonance as a result of geometric scattering. Using this technique on simulated bubble data showed the matrix to be very poorly conditioned (typically of the order of 10^4), and to improve this a minimum second derivative 'smoothness' constraint was appended to the data before inversion [5].

2. FIRST DEPLOYMENT DETAILS

The first deployment of the apparatus used a combination frequency measurement technique only, and a layout of the deployment buoy and schematic of the apparatus are given in figures 1(a) and (b) respectively.

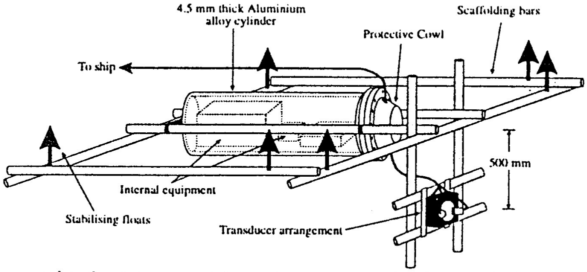


Figure 1(a): Deployment details of the watertight canister and buoy for the first deployment.

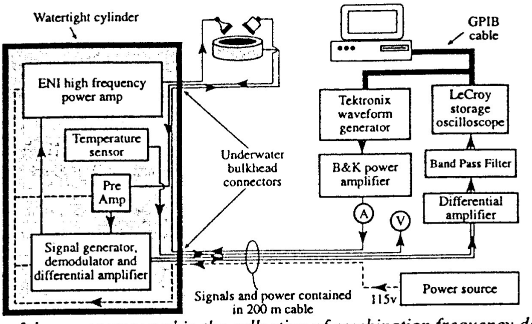


Figure 1(b): Schematic of the apparatus used in the collection of combination frequency data.

The equipment set up was designed such that the focus of the transducer was 0.50 m below the surface of the sea. The calibration procedure, required to relate the height of the scattered sum-and-difference signals to the number of resonant bubbles, is detailed elsewhere [2,3]. The buoy itself was deployed in the Solent on the 27th June 1997, in water whose depth ranged from 17 to 22 m and in (unseasonally high) wind speeds between 10 - 12 m/s, gusting up to 16 m/s. From consideration of the dominant wave period and water depth, it was determined that the data was collected in water that can be considered to be deep (using an oceanographic definition). Six runs consisting of ten 'snap-shots' of the bubble population at each of the ten frequencies were taken, and the time averaged population corresponding to one of the runs is shown in figure 2 compared with four historical measurements of deep water bubble populations [6-9].

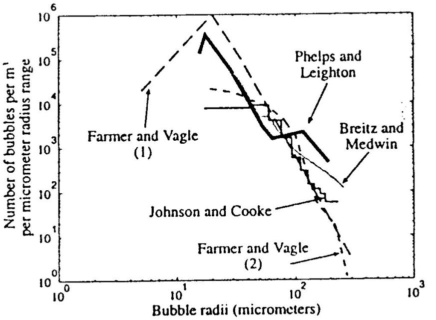
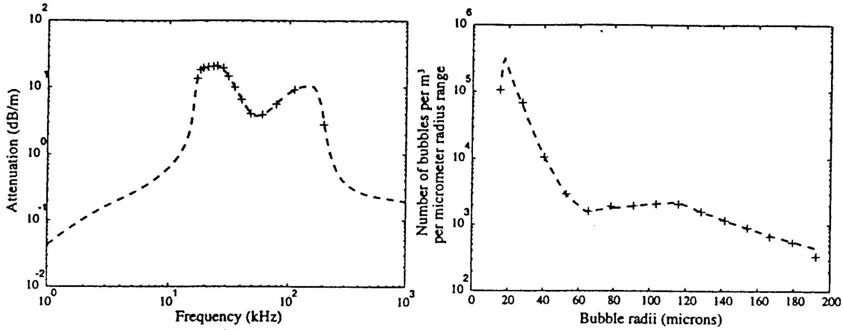


Figure 2: Comparison of time-averaged data measured in deep water using the sum-and-difference technique (thick unbroken line), with historical estimates taken from references [6-9].

The efficacy of the inversion technique can be best demonstrated on this measured bubble population. Using procedures detailed by Commander and Prosperetti [10], the excess frequency dependent attenuation which the bubble population represents was calculated, and 15 discrete attenuation values from this calculation were then used in the matrix inversion routines described earlier. The plot of excess attenuation over a broad frequency range is shown in figure 3(a) (with the 15 discrete values used in the inversion shown as crosses) and the results from the inversion routines shown in figure 3(b) compared with the original measured data.

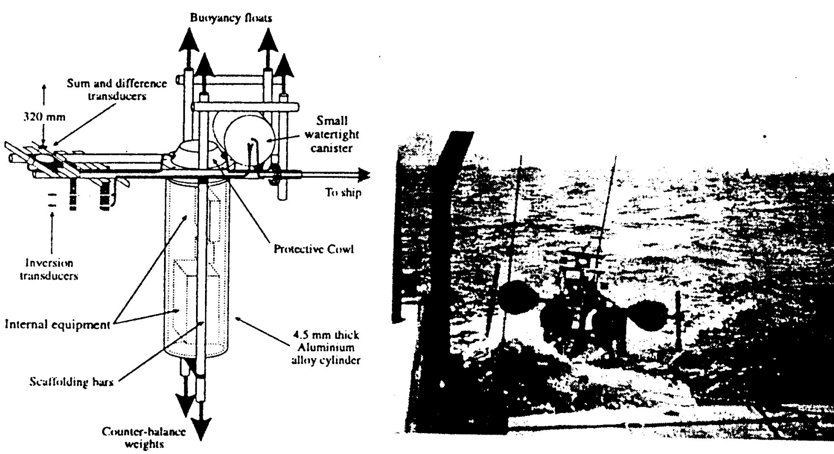


(a) (b)

Figure 3(a): Excess frequency dependent attenuation calculated from the first deployment sea data, with the discrete values used in the inversion technique shown as crosses: (b) Results from using these attenuation estimates in inversion routines (crosses) compared with original data.

3. SECOND DEPLOYMENT DETAILS

The second deployment of the apparatus used both the combination frequency measurement technique and the additional hydrophones necessary to perform the finite element inversion. The redesigned layout of the buoy, a photograph of the rig upon deployment, and a schematic of the additional apparatus which was employed are shown in figures 4(a) to (c).



(a) (b)

Figure 4(a): Deployment details of the watertight canister and buoy for the second deployment: (b) Photograph of the rig upon deployment from the back of the research vessel.

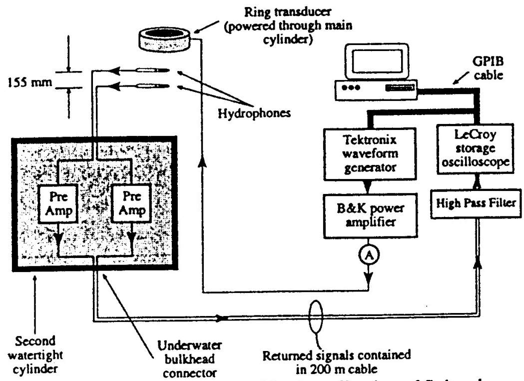


Figure 4(c): Schematic of the additional apparatus used in the collection of finite element inversion data.

From a practical consideration, there are several benefits to using an inversion technique. First, the amount of equipment required to perform the tests is much reduced, requiring (in these tests) only two Bruel and Kjaer 8103 hydrophones conditioned with type 2365 preamplifiers in the remote buoy. Second, there are none of the problems associated with calibrating the equipment beforehand to be able to relate the signal strength to bubble number, as the input to the inversion routines is simply the acoustic signal loss between two identical hydrophones. Thus, any equipment in the returned signal path with a variable frequency response (e.g. the preamplifiers, 200 m cabling, etc.) will not affect the acoustic loss measurements as long as it is equal for both hydrophone paths.

The second deployment was performed on the 24th April 1998. However, due to recent restrictions on tests using the particular research vessel, the buoy was deployed in Southampton Water instead of in the Solent itself, and in lighter wind speeds than the first trials. Thus, the tests were in oceanographically shallow water (7 m) at wind speeds of 7-8 m/s, and without the long fetch required for breaking waves. The results from one of the four combination frequency tests are shown in figure 5.

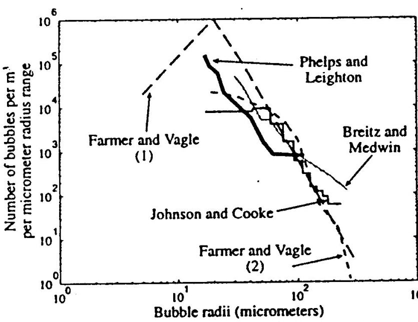


Figure 5: Comparison of time-averaged data measured during the second deployment using the sum-and-difference technique (thick unbroken line), with historical estimates taken from references [6-9].

It is important to emphasise the difference between the data in figures 2 and 5. Whilst the former records absolute bubble counts, the data from the second sea trial showed very few actual bubble signals evident in the collected data during the processing. Rather, the plot demonstrates the limit of sensitivity of the apparatus and automated counting technique, as most of the signal which the processing considers to be bubble information is actually measurement noise in the returned signal [3].

Unfortunately, in addition to the lack of bubble information collected using the sum and difference technique, the two hydrophones which were employed to measure the dispersive acoustic losses required in the inversion tests were impacted against the side of the ship upon deployment. This resulted in one being broken, and the second being bent considerably out of place. Data using the second hydrophone was still collected, and it is hoped that it may be possible to retrieve useful information from this by re-floating the rig in bubble-free water in a test tank and measuring the non-bubble mediated signal strength using the same input conditions. This will allow an excess attenuation to be calculated, which would be due to the oceanic bubble population. However, the limitations of the relatively bubble-free environment in which the oceanic data was collected may preclude useful population estimates from being calculated even after this post-calibration.

This work was funded by the Natural Environment Research Council, ref GR3 09992.

REFERENCES

[1] T.G. Leighton, *The Acoustic Bubble*, pub. Academic Press, London (1994)

[2] A.D. Phelps, D.G. Ramble and T.G. Leighton, "The use of a combination frequency technique to measure the surf zone bubble population", *J. Acoust. Soc. Am.* **101**, 1981-1989 (1997)

[3] A.D. Phelps and T.G. Leighton, "Oceanic bubble population measurements using a buoy deployed combination frequwncy technique", *IEEE J. Oceanic Eng.* In press (1998)

[4] K.W. Commander and R.J. McDonald, "Finite-element solution of the inverse problem in bubble swarm acoustics", *J. Acoust. Soc. Am.* **89**, 592-597 (1991)

[5] S.D. Rajan, "An inverse method for obtaining the attenuation profile and small variations in the sound-speed and density profiles of the ocean bottom", *Ph.D. Thesis*, pub. Cambridge and Woods Hole, Massachusetts (1985)

[6] D.M. Farmer and S. Vagle, "Waveguide propagation of ambient sound in the ocean-surface bubble layer", *J. Acoust. Soc. Am.* **86**, 1897-1908 (1989)

[7] B.D. Johnson and R.C. Cooke, "Bubble populations and spectra in coastal waters; a photographic approach", *J. Geophys. Res.* **84**, 3761-3766 (1979)

[8] N. Breitz and H. Medwin, "Instrumentation for in situ acoustical measurements of bubble spectra under breaking waves", *J. Acoust. Soc. Am.* **86**, 739-743 (1989)

[9] D.M. Farmer and S. Vagle, "Bubble measurements using a resonator system", in *Natural physical processes associated with sea surface sound*, ed. T.G. Leighton, pub. University of Southampton, UK, 155-162 (1997)

[10] K.W. Commander and A. Prosperetti, "Linear pressure waves in bubbly liquids: comparison between theory and experiments", *J. Acoust. Soc. Am.* **85**, 732-746 (1989)