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LOW-FREQUENCY SCATTERING FROM RESONANT BUBBLE CLOUDS

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INTRODUCTION

Studies indicate that microbubble layers and bubble plumes are produced when waves break and are subsequently convected to depth by Langmuir circulation [1]. We seek to explore the role that plumes play in the near-surface scattering of low-frequency (<2 kHz) sound. Prosperetti [2] and Carey *et al.* [3] argue that it is not the individual bubbles driven at their natural resonance frequencies that contribute the most to the low-frequency scattering cross section of a bubble plume. Rather, sound is scattered by the plume itself via a process in which the bubbles pulsate collectively and the acoustic propagation is determined by the mixture properties; the bubbles establish compressibility and the water provides inertia. A resonance response results in which the eigenfrequency is determined by the phase speed within the mixture and the size of the plume. Evidence of this phenomena has been obtained from the study of noise from steady-state bubble columns [4].

We report preliminary results, obtained on-line, from an experiment designed to measure acoustic backscattering from a bubble cloud in fresh water in the absence of boundaries and under known propagation conditions. In this effort we did not set out to duplicate "realistic" salt-water bubble clouds, but rather to obtain data to test bubble cloud scattering theories in order that ocean experiments could be more effectively conceived.

EXPERIMENTAL APPARATUS AND PROCEDURES

The NUWC Seneca Lake, NY test facility consists of two moored barges in 130 m of water, with the smaller barge (10.7 m x 42.7 m) serving as the platform for our test range. Equipment was deployed with the use of davits, a cable meter, and the edge of the barge, with the resulting vertical geometry shown in Fig. 1. Parametric and conventional transmitters and conventional receivers were orientated collinearly, with the axis of the range intersecting the path of a rising bubble cloud. Though the actual test consisted of measurements for frequencies ranging from 300 Hz to 14 kHz, only the low-frequency (< 1.5 kHz) results will we presented here.

The parametric source (PS) was driven with a 22-kHz carrier signal which was up and down-shifted by 1/2 the difference frequency. The repetition frequency was fixed at 2 Hz and the pulse length varied from 5 to 10 msec. Calibration of the source characteristics was performed *in situ*. At 500 Hz, the beamwidth and source level was 8.5° and 167 dB *re* 1 μPa respectively.

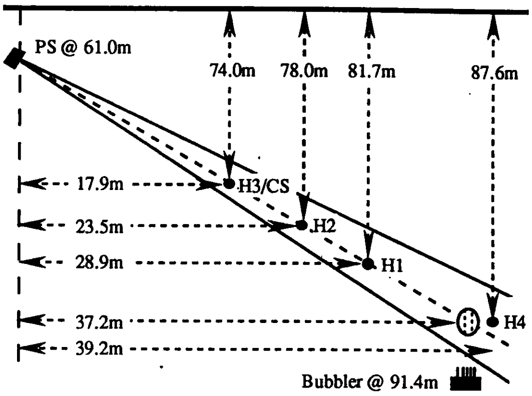

Figure 1. Test range for the backscattering experiment.

Although parametric sources have the advantage of low-frequency directionality, bubbly liquids are highly nonlinear and there is a possibility of an "apparent" elevation in the measured backscattering due to enhanced parametric interaction within the cloud. In response to this, a Honeywell HX-29 conventional source (CS) was also utilized. The working depth of 87.6 m was chosen to minimize reverberation.

Our receivers consisted of four ITC 6" spherical hydrophones, situated as indicated in Fig. 1 (see H1 thru H4). All hydrophone outputs were band-pass filtered, preamplified, and recorded on analog tape.

Sound speeds were measured daily during the test. For depths greater than 70 m isovelocity conditions prevailed, with speeds of 1421.7 m/sec & 1420.8 m/sec at 70 m & 91.4 m respectively. For the calculations that follow, a speed of 1421.5 m/sec was used.

We aligned the range using the 22-kHz signal to measure time-of-flight and verify alignment and slant ranges. We then inserted a 1.12-m diameter, hollow, steel spherical target in order to test our ability to measure target strength (TS) [5]. Assuming a perfectly reflecting surface, this sphere possessed a theoretical TS of -11.1 dB at 5 kHz. Our measured TS was -12.3 dB.

Bubble clouds were produced at 91.4-m depth using a pressurized steel enclosure, vented to the lake via a 2-D circular array of 48, 22-gauge hypodermic needles connected to a bank of 24 solenoid valves. A 3.5-sec burst of air at 10 psi overpressure yielded a roughly cylindrically shaped cloud (length ≈ 1.4 m, diameter ≈ 0.5 m) with a void fraction of ≈ 0.0025. The bubble sizes (measured with a video camera at depth) were distributed about a peak at 1.55-mm radius, which corresponds to $f_0 \approx 6.8$ kHz at a depth of 87.6 m.

The cloud rose at ≈0.3 m/sec, yielding a time-varying echo that reached a maximum level as the cloud crossed the range axis. We monitored the evolution of the echo level by digitizing the time-gated echo return, storing subsequent returns in memory, and displaying a time-compressed view of the sequence of echo's produced by the passage of a single cloud, as shown in Fig. 2.

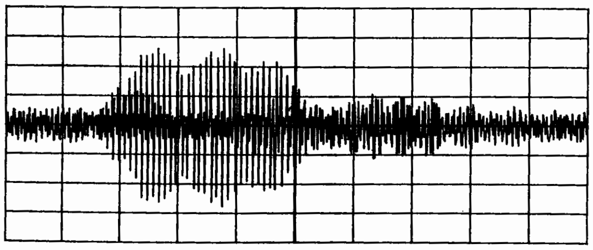

Fig. 2 A time-compressed view (5 sec/div) of the echo level produced by a cloud rising through the PS-beam operating at a 3.0 kHz difference frequency.

The echo corresponding to the maximum response was chosen for the determination of target strength. We measured the peak-voltage of the main pulse (MV) and the echo (EV) and inserted these quantities, along with the transmission loss factor (TLF), into the following expression for the target strength:

$$TS = 20 \log [EV/MV] - TLF; \quad TLF = TL_{sr} - TL_{st} - TL_{tr} \quad (1)$$

where the TLF accounts for source-receiver, source-target, and target-receiver transmission losses, assuming spherical spreading of the propagating waves [5]. Target strengths presented below consist of either single measurements or the average of 2-3 measurements. Comparisons of repeated measurements indicate fluctuations in the TS which ranged from ±0.5 dB to ±3 dB.

RESULTS AND DISCUSSION

Target strength measurements obtained using conventional and parametric sources are plotted in Fig. 3. The target strengths are very high; at 500 Hz, the TS is about 10 dB greater that one would expect from a 1-m diameter perfectly reflecting sphere. There are apparent resonance peaks at 1.3 kHz, ≈ 950 Hz, and ≈ 450 Hz. If these peaks were due to single-bubble resonance scattering, the bubbles would possess radii of 8.2 mm, 1.0 cm, and 2.1 cm respectively, which is highly unlikely.

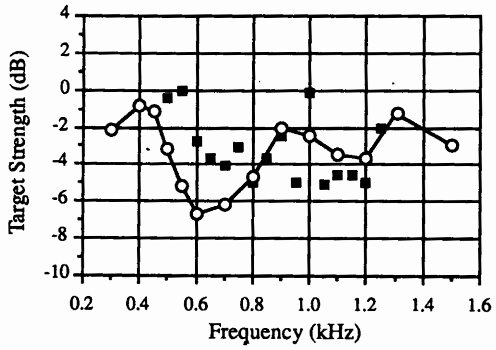

Fig. 3 Backscatter target strength measurements for conventional (squares) and parametric (circles) sources.

It is probable that these peaks are the result of resonance scattering due to collective oscillations of the bubble cloud. The resonance frequency for a spherical bubble cloud is approximated by [3],

$$f_o \approx \frac{1}{2\pi a}\left[\frac{3\gamma P_o}{\chi(1-\chi)\rho}\right]^{1/2} \quad (2)$$

where χ, γ, P_o, ρ, and a are, respectively, the void fraction, the polytropic exponent, the ambient pressure, the water density, and the cloud radius. A cloud with a void fraction of 0.0025 and an "effective" radius of 0.5 m (1/2 the average of the cloud diameter and the cloud length) has a resonance frequency of 405 Hz. Moreover, the target strength is given by [5]:

$$TS = 10 \log [I_s/I_i]_{r=1\,m} \quad (3)$$

where I_s and I_i are the scattered and incident intensities respectively. To lowest order, this is given by [3]:

$$I_s/I_i \approx \frac{z_o^{\,6}}{9}\,\frac{\{1-(x/x_m)\}^2}{\{1-(x/x_m)z_o^{\,2}/3\}^2 + \{(x/x_m)z_o^{\,3}/3\}^2} \quad (4)$$

where z_o=ka, x=ρc^2, and $x_m=\rho_m c_m^2$; the subscript denotes the effective properties of the air/water mixture [6]. For a 0.5-m radius cloud with a void fraction of 0.0025, Eqs. 3 and 4 yield a TS of -2.5 dB @ 405 Hz. These values are consistent with our measurements near 450 Hz.

Parametric and conventional measurements exhibit "reasonably" good agreement despite the fact that reverberation made it difficult to obtain CS data for frequencies less than 1 kHz. It appears that enhanced parametric excitation in the region occupied by the bubbly fluid did not serve to appreciably bias the TS measurements.

CONCLUSIONS

Measurements of target backscatter versus frequency have been made using both conventional and parametric sources. The results using these two types of sources were found to be comparable for frequencies ranging from 300 Hz to 1.5 kHz. Backscatter TS were quite high, exceeding that of a comparably sized, perfectly reflecting sphere by as much as 10 dB. Peaks in the TS spectrum at 500 Hz, 950 Hz, and 1.3 kHz are suggestive of cloud resonances due to collective oscillations and are apparently independent of the bubble size distribution. Resonance scattering calculations exhibit quantitative agreement with TS data obtained near 450 Hz. This work was performed at the NUWC Seneca Lake test facility and supported in part by ONR, ONT, AEAS, and NUWC/IR.

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