Carey, W.M. and Roy, R.A., "Radiation and scattering from micro-bubble clouds," *Proceedings of the 17th International Congress on Acoustics, September 2001.*

Radiation and Scattering from Micro-Bubble Clouds

W. M. Carey and R. A. Roy

Department of Aerospace and Mechanical Engineering, Boston University, Boston, MA 02215 USA

The radiation and scattering from micro-bubble clouds with volume fractions greater than .01% are described using a theoretical model and measured data. In the low frequency limit, the radiation and scattering of sound was determined to be monopole when in the free field. The natural frequency of the cloud is predicted by a modified Minnaert equation. The measured backscatter target strength is consistent with calculations. Both the production of sound by breaking waves and sea surface scattering is affected by these micro-bubble clouds either in whole or in part. Since these features are compact at the lower frequencies, a multipole expansion shows that the most important response is the monopole and its surface image. [Work supported by ONR.]

INTRODUCTION

Micro-bubble plumes, clouds and layers are produced when waves break. The fundamental question asked a decade ago was: what role, if any, is played by these micro-bubble plumes in the production and scattering of sound near the sea surface from the low (20 Hz) to mid (2 kHz) frequency range? Ocean ambient noise showed a dramatic increase in mid-frequency ambient noise levels when wave breaking occurred. Furthermore, sound scattered from the sea surface at the second convergence zone revealed a target like characteristic with a large zero Doppler component. If micro-bubble clouds and plumes with void fractions greater than .01% act as collective resonant oscillators, then radiated noise can be produced and scattering can occur with little Doppler shift but ample spread. That is, a large number of micro-bubbles with individual resonance frequencies far above the frequency of excitation and occupying an acoustically compact region, acts like a uniform compressible fluid. [1-3]

THE COMPACT BUBBLY SPHERE

In a bubbly liquid, where bubble resonance frequencies are much greater than the frequencies of interest, the propagation obeys an "effective" wave equation for a medium with a mixture density and sound speed. For air bubbles in water with volume fraction, χ, and with size and spacing small compared to a wavelength, c_{mlf} is the low frequency (LF) limiting sound speed given by the following equation:

$$c^2_{mlf} = P\gamma/[\rho_\ell \chi(1-\chi)],\ 0.002<\chi<0.94\ , \qquad (1)$$

where P is the ambient pressure and γ is the ratio of specific heats. The scattering of sound from a compliant sphere, cloud, is classical.[1] It has no well-defined boundary, is compact, and composed of micro-bubbles with resonance frequencies, f_{ob}, far above the frequency of excitation, f_e. The properties of the bubbly region are given by an effective sound speed, c_{mlf}, and density, ρ_m. The source of excitation is global compared to the dimensions of the compact cloud, an incident plane wave, and the boundary condition is continuity of normal velocity and pressure at the generalized radius, r_o. The procedure is to assume the scattered wave is a sum of outward propagating spherical waves with coefficients A_m. When $\lambda > 2\pi r_o$ and for the above boundary conditions:

$$A_0 = \frac{\frac{i}{3} P_0 (kr_0)^3 (1-y)}{\left[1 - \frac{1}{3} y (kr_0)^2\right] - \frac{1}{3} i y (kr_0)^3}\ , \qquad (2)$$

where $y = (\rho c/\rho_{\square} c_{mlf})$. A resonance condition for the fundamental frequency of the cloud results from setting the real part of the denominator in A_o equal to zero, yielding a modified Minneart formula:

$$f_{oc}(2\pi r_o) = \left(3\gamma P/\rho_1 \chi(1-\chi)\right)^{1/2} \cong \left(3\gamma P/\rho_1 \chi\right)^{1/2} \quad (3)$$

Note that f_{oc} is proportional to the compressibility of the bubbly region, characterized by the stiffness ($4\pi r_o \overline{\rho c}^2$), and to the inertia ($4\pi r_o^3 \rho/3$).

NOISE EXPERIMENTS [1-3]

Two noise experiments were performed with fresh water, FW, and salt water, SW, under known vf and bubble size distributions. The tipping trough experiment simulated a breaking wave event at Seneca Lake and at Dodge Pond. Transient spectral results showed a prominent LF spectral peak near 100 Hz for both FW and SW with the SW spectrum level (SWSL) less than the FW spectrum level (FWSL) by 3 dB. Most events produced clearly dampened singular sinusoids. With initial potential energy of 123–169 J, the radiated sound energy was 0.4–2.5 10^{-6} J with radiation efficiencies between 0.3–2.26 10^{-8}. The f_{oc} was between 90 and 120 Hz. The second experiment was performed with FW, Lake Washington, and SW, Puget Sound. A cylindrical "slug" of water upon impact resulted in a separated, nearly-spherical bubble cloud accompanied by the sudden -pronounced LF emission. Similar FWSL and SWSL at the LF resonance were observed. When the FW and SW vfs were similar, the frequency of the emission at resonance agreed with f_{oc}. SWSLs were found to be lower than the FWSL. These spectral differences state that, for a constant vf, the ratio of the thermal loss of FW to SW is the ratio of the mean bubble sizes.

BACKSCATTER

The Seneca Lake test used parametric, conventional sources and conventional receivers along the axis of the range intersecting the path of a rising bubble cloud. Although parametric sources have the advantage of LF directionality, bubbly liquids are nonlinear and possible enhanced-parametric-cloud interaction was examined by comparison with conventional source results. Clouds were produced at 91.4-m depth using a pressurized enclosure, a concentric circular array of needles and a bank of solenoid valves. A roughly cylindrically shaped cloud (length ≈ 1.7 ± 0.3 m, radius ≈ 0.24 ± 0.01 m, and a vf of 0.55 ± 0.01%) were produced. The bubble frequencies were normally distributed about a peak $f_{ob} \approx 9.2 \pm 1.7$ kHz. The clouds rose at ≈ 0.3 m/sec, yielding a time-varying echo that reached a maximum level as the cloud crossed the range axis. A measured transmission loss factor enabled TS to be determined to be ≈ 1 dB between 300–350 Hz. The calculated $f_{oc} = 324 \pm 53$ Hz with $\chi = 0.55\%$ and $r_o = 0.38$ m compares to measured values between 300–350 Hz. Moreover, calculations using the definition of A_o yielded a $TS_c = -4 \pm 0.5$ dB at 325 Hz. There was an apparent interference pattern near 300 Hz due to reflection from the bubbler which when accounted increased the TS by 4.8 dB to 0.8 dB in agreement with measurements.

CONCLUSIONS

The evidence for LF-noise generation by breaking waves is now well established. Since larger bubbles are absent, collective oscillation of the entrained micro-bubble cloud is the most plausible explanation. The specifics of an individual breaking wave event are still not known, however, the complex cloud is surely compact at the LFs. This compactness allows a simplification of the mathematical description as a sum of a monopole, dipole, and quadrupole sources under a pressure release surface. The monopole and its image have a dipole radiation pattern. The simplest representation which ensures a dipole pattern and enables the average source strength to be determined from measurements, is a monopole of known strength a quarter wavelength below the surface.

The sea surface scattering problem was to explain "spiky" returns from the second convergence zone with a "zero Doppler" shift as well as the direct LF scattering measurements of Chapman-Harris and Chapman Scott. They recognized that at the higher frequencies the direct scatter results required the presence of bubbles beneath the pressure release surface. However the LF scatter required a bubble layer, large bubbles, bubble clouds or combinations.

We have shown that compact bubble clouds can behave as monopole scatters. Recent evidence also shows the presence of "isolated , acoustically-strong highlights seen in broad band data at all wind speeds" and images clearly show discrete scatters with short lifetimes. While sound scattering from bubble clouds may not be the only mechanism required to explain the levels of the Chapman-Harris curves, it is certainly true that the scattering from bubble clouds describes the discrete nature of sea surface scattering. Furthermore since the clouds and plumes stay put beneath the breaking waves, such features would have zero Doppler shift but ample Doppler spread.

REFERENCES

1. W. M. Carey, R.A. Roy, "The Low Frequency Radiation and Scattering of Sound from Bubble Clouds", in *Proc. of the MTS/IEEE Oceans 2000*, Providence, RI (2000).

2. W.M. Carey, R.A. Roy, " Sound Scattering from Micro-bubble Distributions Near the Sea Surface" in *Ocean Reverberation,* ed. By D.Ellis, Kulwer, 23-43 (1993).

3. R.A Roy, W.M Carey, "Acoustic scattering from bubble clouds", in *Natural Physical Processes Associated with Sea Surface Sound*, ed. by T.G. Leighton, ISVR, Univ. Southampton, 221-231, (1997).