Historical Measurements of Bubbles in Coastal Environments: Effects of Biogenic Bubbles on Propagation of High Frequencies

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Abstract

The presence of microbubbles can have a significant effect on sound attenuation, refraction, dispersion, and phase fluctuations during high frequency propagation in coastal waters. Early research by students at the U.S. Naval Postgraduate School measured large populations of coastal bubbles, apparently generated by biological activity in nearly calm conditions, that appeared to be omnipresent within many meters of the sea surface. These biogenic bubbles supplement the bubbles due to rain and breaking waves, which have received much attention recently.

1. Introduction

In the 1960's a program of student experimental research was initiated at the U.S. Naval Postgraduate School to answer the question asked by a U.S. Navy Oceanographer "Do Invisible Bubbles Exist in the Sea?" The answer turned out to be an emphatic "yes". The research was conducted between 1964 and 1974 by a succession of ten students, each with a different experimental project which served to fulfill his thesis requirement for the M.S. degree. The methods used were standard physical acoustics techniques, common to laboratory studies of structural and molecular characteristics of gases, liquids, and solids; the same type of measurements in the ocean were inverted to yield bubble densities, sound speed dispersion, and phase fluctuations.

These first measurements of bubbles at sea were summarized in [1–4]. The publications dealt with the interpretation (as due to *in-situ* bubbles) of excess sound attenuation, dispersion, and phase fluctuations on experiment depth, frequency, time-of-day, season, presence of sea slicks, instantaneous wave height, and wind speed. The early research, most of which was conducted for convenience in shallow coastal waters during nearly calm seas, revealed very large numbers of bubbles. The experimental evidence of these omnipresent populations of coastal bubbles of resonance frequencies from 20 to 200 kHz, strongly suggests that they are due to biological activity in the volume and at the bottom. Some bubbles may also be caused by continental aerosols when they fall into the sea.

To our knowledge no one has gone beyond these coastal bubble measurements which were published over two decades ago.

2. Bubble Theory

A bubble of gas ratio of specific heats γ, and radius a in water of ambient density ρ_A at ambient pressure p_A, can resonate to an incident acoustic wave of frequency f_b because of its oscillating mass (the water in the skin surrounding the bubble) and its stiffness (due to the compressibility of the gas). The result is a natural pulsation frequency given by

$$f_b = \frac{1}{2\pi}\sqrt{\frac{s}{m}} = \frac{1}{2\pi a}\sqrt{\frac{3\gamma p_A}{\rho_A}}\ , \tag{1}$$

which allows one to specify the radius of the bubble resonating to the incident frequency f. Linear theory shows that there will be a frequency-dependent bubble damping constant at resonance δ_R of order 0.1 due to thermal conductivity, shear viscosity, and reradiation of the sound. At resonance, this will cause a scattering cross section, absorption cross section, and extinction cross section, of order 10^2 times the geometrical cross section. (The backscattering cross section is the ratio of the backscattered power to the incident intensity. The scattering is omnidirectional at resonance.) The result is backscatter and excess attenuation compared to bubble-free water.

Linear theory also shows that the compressibility of a bubbly medium leads to a complex propagation constant with velocity dispersion as well as attenuation, see Fig. 1. The deviation of the sound speed from that measured by a sound velocimeter (which operates in the megahertz range) depends on the bubble density and the ratio of the incident frequency to the bubble resonance frequency. At frequencies much greater than the resonance frequencies of the predominant bubbles, the speed is equal to the value obtained from a sound velocimeter. At frequencies much less than the resonance frequency of the largest bubbles, the speed depends on the void fraction of the medium and can deviate by tens of meters per second from the bubble-free medium. There will be a fluctuation in the phase of transmitted sound that depends on the variation of the number of bubbles per unit volume $c(u)$ as well as the change of resonance frequency [i.e., due to a change of ambient pressure $c(z)$ in (1)] and the damping constant δ_R. See bottom of Fig. 1, which is based on theory in reference [13].

3. Measurement Techniques

The first measurements of bubble densities at sea consisted of photographing and then counting and sizing the bubbles in a volume of about one cubic centimeter [5]. We then proceeded to the more promising acoustical tests.

The linear acoustical techniques for measuring ocean bubble densities depend on the appropriate inversion of the distinctive effects of insonified bubbles [6] and consist of employing many frequencies to determine bubble densities for many radii in the range $20\,\mu$m to $200\,\mu$m. In the period from 1964 to 1974 they included:

a) excess attenuation in a pulse-echo system in which a low Q, 30 cm diameter, mylar transducer faced a 30 cm diameter rigid reflector at a separation of about 100 cm; the transducer radiates a tone burst and then is switched to receive the series of echoes which follow;

b) measurement of the relative backscatter compared to reflection in the pulse-echo system;

c) travel time between echoes, for different frequencies in the pulse-echo system;

d) ratio of amplitudes at two point receivers at separation of the order of meters in the field of a frequency-variable source;

e) difference of phase at two point receivers separated by one to five meters in the field of a frequency-variable source.

Much later an effective one-dimensional multi-frequency acoustical resonator technique was pioneered by Breitz and Medwin [7, 8] for measurements close to the surface of breaking waves. The device has recently been improved by others and used to obtain much data under a variety of breaking wave conditions at sea. It could also be used in coastal waters, of course.

In the early 1970's, measurements were also made of the spectral density of sound phase modulation during propagation in bubbly water [2, 3]. Prominent bubble populations cause phase shifts that mimic the spectral density of ocean surface wave displacements, which are the source of ambient pressure changes that create shifts in the bubble resonance frequencies described by (1); see the 95.6 kHz data in Fig. 2. On the other hand, randomly variable void fractions cause a Gaussian spectrum of phase fluctuations as demonstrated by 24.4 kHz in Fig. 2.

4. Empirical Bubble Densities in Quiescent Coastal Waters

Based on measurements by Medwin [1, 4], and separate analysis by P. J. Mulhearn [9], and J. C. Novarini and G. V. Norton [10], it is possible to describe the form and speculate about the causes of bubble densities as a function of bubble radius and depth in quiescent coastal waters. Figures 3 and 4 tell a complex story. Figure 3, from [4], is a summary of results, measured in mid or late afternoon, at approximately the same depths, during different months of the year, under similar meteorological and oceanographic conditions, in Monterey Bay, CA and San Diego Bay, Ca, approximately 700 km to the south. The slope of bubble density vs. radius changes at approximately 40 to 60 microns bubble radius. Figure 4 shows that there is a depth dependence that is different for high frequencies (small bubbles) and low frequecies (larger bubbles). Using both figures, the density can be described by

$$n(a)da = K_1 \left(\frac{a}{60}\right)^{-2} (z)^{-1/2} \quad \text{for} \quad 200\,\mu\text{m} > a > 60\,\mu\text{m} \tag{2}$$

$$n(a)da = K_2 \left(\frac{a}{60}\right)^{-4} e^{-z/L} \quad \text{for} \quad 10\,\mu\text{m} < a < 60\,\mu\text{m} \tag{3}$$

where

a = bubble radius in microns;
$n(a)da$ = number of bubbles in a 1 micron increment, per meter^3;
L = small bubble folding depth $\cong 7$ m;
$z \geq 1.5$ m = depth in meters ,

and K_1 and K_2 are constants that depend on the time of day and season.

Figures 3 and 4 show rough averages based on many measurements. There appears to be a definite dependence on season, as would be expected for biological sources of bubbles. The fact that small bubbles are more prominent in the daytime than at night is ascribable to photosynthesis. The evidence that larger bubbles are more dense at night than in the daytime may be due to continental aerosols carried off-shore by night "sea breeze" or may be due to increased biological activity at the sea floor. To add to the complexity of the coastal situation, there is evidence that bubble densities will be greater under sea slicks and windrows, and are even affected by the presence of fog [4]. Bubble densities in other locations with different flora and fauna will be very different. There will also be a wind dependence and a dependence on distance from the surf zone due to breaking waves.

5. Conclusions

Historical measurements of bubble densities and bubble-derived phase modulations of high frequency sound strongly suggest that the effects of biogenic bubbles should be included in propagation models even in nearly calm coastal waters. Once they are known, values of coastal ocean bubble densities may be used to obtain estimates of the acoustical parameters, sound attenuation, backscatter, and dispersion, by application of formulas in books such as references [11, 12].

References

[1] H. Medwin, "*In-situ* acoustic measurements of bubble populations in coastal waters," *J. Geophys. Res.*, vol. 75, pp. 599–611, 1970.

[2] H. Medwin, "Acoustic fluctuations due to microbubbles in the near-surface ocean," *J. Acoust. Soc. Am.*, vol. 56, pp. 1100–1104, 1974.

[3] H. Medwin, J. Fitzgerald, and G. Rautmann, "Acoustic miniprobing for ocean microstructure and bubbles," *J. Geophys. Res.*, vol. 80, pp. 405–413, 1975.

[4] H. Medwin, "*In-situ* measurements of microbubbles at sea," *J. Geophys. Res.*, vol. 82, pp. 971–976, 1977.

[5] P.D.C. Barnhouse, M.J. Stoffel, and R.E. Zimdar, "Instrumentation to determine the presence and acoustic effect of microbubbles near the sea surface," M.S. Thesis, U.S. Naval Postgraduate School, 1964.

[6] H. Medwin, "Acoustical determinations of bubble-size spectra," *J. Acoust. Soc. Am.*, vol. 62, pp. 1041–1044, 1977.

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

[8] H. Medwin and N.D. Breitz, "Ambient and transient bubble spectral densities in quiescent seas and under spilling breakers," *J. Geophys. Res.*, vol. 94, pp. 12,751–12,759, Sept. 15, 1989.

[9] P.J. Mulhearn, "Distribution of microbubbles in coastal waters," *J. Geophys. Res.*, vol. 86, pp. 6429–6434, July 1981.

[10] J.C. Novarini and G.V. Norton, "Acoustic index of refraction in the background bubble layer of the ocean; an updated bubble spectrum and the computer program CBUBBLY," Naval Research Lab report, NRL/FR/7181-93-9432, March 10, 1994.

[11] C.S. Clay and H. Medwin, *Acoustical Oceanography*, John Wiley, New York, 1977.

[12] H. Medwin and C.S. Clay, *Applied Ocean Acoustics*, in preparation 1997.

[13] P.C.C. Wang and H. Medwin, "Stochastic models of the scattering of sound by bubbles in the upper ocean," *Quart. J. of Appl. Math*, pp. 411–425, Jan. 1975.

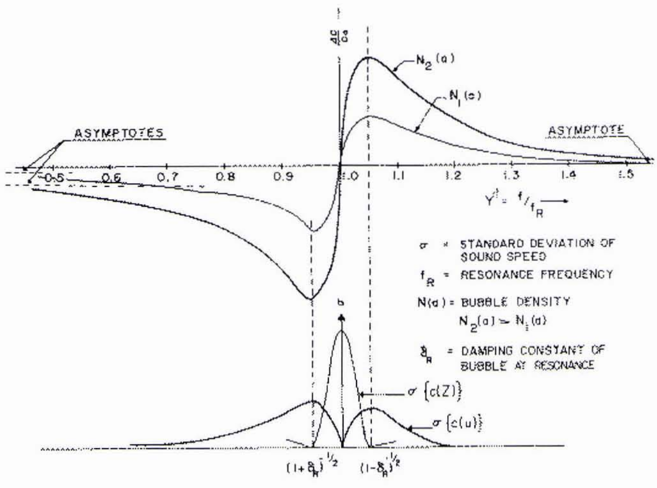

Fig. 1. Sound speed dispersion as a function of ratio of insonifying frequency f to bubble resonance frequency f_R for a mono-radius bubbly region. The bubble density $N_2 > N_1$. The standard deviation of the sound speed depends on whether the speed change is due to change of the number of bubbles, *c(u)*, or due to change of pressure *c(z)*. See Reference [13] for details.

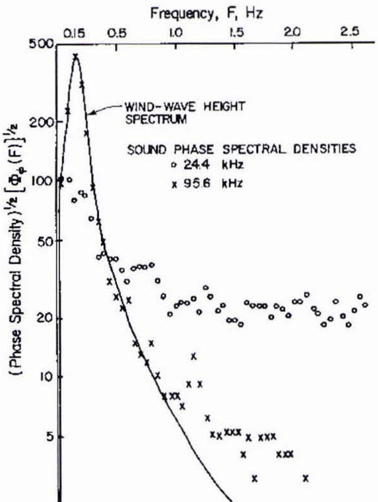

Fig. 2. Spectral density of the phase change due to a mixed population of bubbles. The theoretical wind-wave height spectrum for a Pierson-Moskovitz sea is the solid line. The phase spectral density is nearly Gaussian when the source of change is the random change of void fraction (at 24.4 kHz). It is closely correlated to the wind-wave height spectrum when the phase shifts are due to pressure changes (at 95.6 kHz). See Reference[3] for details.

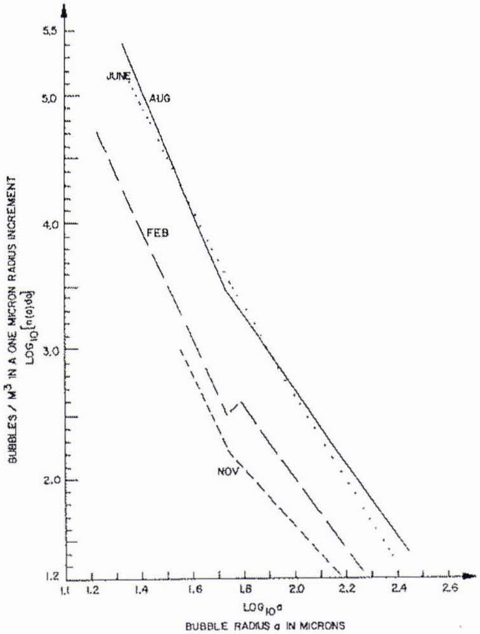

Fig. 3. Seasonal change of bubble density at low wind speeds and 3 to 8 meter depths in late or mid- afternoon. See Reference[4] for details.

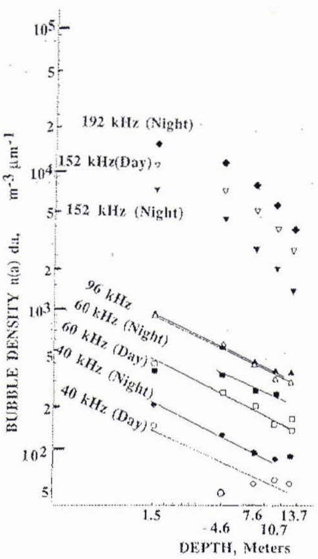

Fig. 4. Bubble densities in coastal waters as observed by high frequency acoustical measurements, as a function of *in-situ* depths from 1.5 to 13.7 m during day and night experiments in February 1965. See Reference[1] for details.