17th SYMPOSIUM ON HYDROACOUSTICS
Jurata May 23-26, 2000

THE ROLE OF GAS BUBBLES IN THE ACOUSTICAL OCEANOGRAPHY

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The paper below presents different aspects of influence of subsurface bubble population on acoustical environment. The role of bubbles in ambient sea noise emission, reverberation processes and signals transmission is presented. The attention has been devoted to specific properties of the Baltic Sea water and its influence on bubble population.

1. INTRODUCTION

At wind speeds higher than a few meters per second, usually 6-7 m/s, when breaking waves are observed, the agitation of the sea surface is accompanied by a dense population of air bubbles forming different space structures, varied in size and in time called the subsurface bubble layer. In addition to the wind dependence portion of bubbles, there exists a background layer of persistent microbubbles with a void fraction on the order of 10^{-8}.

Gas bubbles in the subsurface ocean layer play important role in many physical processes on the atmosphere - ocean boundary. Due to presence of the bubble population the acoustic environment near the sea surface is very different compared to the deeper water layers affecting the propagation of acoustic waves. In hydroacoustics, the bubble population should be taken into consideration as a source of the ambient sea noise, they lowered the sound speed values, are the reason of sound speed dispersion and excessively attenuate acoustical signals. Bubble clouds are recognised as dominant acoustic scattering and reverberation mechanism in the upper ocean layers. The latter effects are due primarily to the high compressibility of the bubbles.

The main source of gas bubbles are breaking surface waves. Bubbles generated at the sea-surface are transferred downwards by flows and the turbulence mixing to depths ranging from 1.2m to 2.0m, and form roughly cylindrical plumes with diameters ranging from 0.5m to 1.0m.One type of breaking waves, the plunging breaker, can entrain large quantities of air bubbles to the maximum penetration depth as large as 10 to 20 meters. The smallest bubbles could be observed at the depths of 50m.

Bubble plumes of various void fractions and sizes are produced also by droplets impinging water surface or while the snow flakes fall.

The other sources of the gas bubbles are: the photosynthesis processes, geochemical processes in the sediments, upwelling.

Gas bubbles, when present in sediments, strongly influence acoustic properties of the sea bottom. At low frequencies the reflection of sound waves from the gassy sediments is similar to the reflection from the water-atmosphere interface.

There is widely known fact that the concentration of gas bubbles in the subsurface layer is wind speed dependent. But, the other worrying fact is that the values of bubble concentrations presented by different authors for the same wind speed show abnormal dispersion of values. As a source of great differences, aside the sea state, other factors must certainly influence the bubble population, among them could be: viscosity of the water (temperature and salinity), gas saturation of surficial seawaters, biological activity and concentration of surface active substances.

2. INFLUENCE OF WATER PROPERTIES ON CONCENTRATIONS AND SIZE SPECTRA GAS BUBBLES.

The question of differences in the gas bubble concentrations in the natural seawater and freshwater was raised by numerous authors.

The salinity and chemical composition of marine water profoundly change the process of microbubble formation. As much as order of magnitude, the increase of the bubble concentration was observed in laboratory for salt water vs. fresh water over the entire radii range .This fact should be accounted in extrapolating oceanic results to the less saline (2 - 8 ‰) Baltic water environment.

Viscosity depending on the temperature and salinity of the natural water influences the intensity of processes of the gas bubble creation. On the other hand, viscosity changes the rising velocity of a bubble lengthening the time of residence in the water body. Surface active substances contribute to the longer persistence of bubbles and in consequence to deeper penetration depth which can account for the higher backscattering level.

The bubble measurements showed that bubble plumes in cleaned freshwater had a higher concentration of large bubbles and a lower concentration of small bubbles than the plumes in cleaned seawater [8,9].

It was found that the general features of spectrum function was (the slope of a straight line fitting a log concentration versus log diameter varied around –2 in both case). However, a more detailed comparison shows considerable differences between seawater and freshwater populations. In the bubble cloud in the seawater bubbles were more numerous, smaller, and stayed longer than in fresh water.

3. BUBBLE SOURCES OF THE AMBIENT SEA NOISE SPECTRA

Entrained in water gas bubbles excited by different mechanisms were recognised as effective sources of sound very early. In his pioneering investigations with streaming bubbles excited by external forces Strasberg [20] reported that emitted by bubble sounds are associated with simple volume pulsation.

It has been known since the 60s [24] that the Knudsen region of the ambient noise spectrum is associated with breaking and spilling waves events. More recent investigations have confirmed the theory that the main mechanism which produces the noise under breakers is free oscillations of bubbles

Even, at low sea states, when there is little no observable whitecapping, capillary waves create bubbles which radiate sound.

Generally, two different mechanisms of noise generation by bubbles are recognised. The first in which noise is generated by single bubbles at their resonance frequencies at high frequencies. The second one are oscillate coherently bubbles inside of clouds. This mechanism emitted sound at low frequencies. The average of individual bubble events yielded a spectrum that slopes at about 5 dB/oct from 1 to 20 kHz, the same as the Knudsen wind noise spectra at sea. The magnitude of the laboratory breaker noise during continual wave-breaking events was approximately 80 dB// 1 μ Pa^2 /Hz at 1 kHz, which is essentially the same as observed during the continual bubble production that occurs with very high winds at sea [13]. Generally, we have no theory which could predict the rate of different output forces excitations. Various alternative theories involving spray impacts and turbulent forcing of bubble oscillations were put forward by many authors. Experimental results which seem to confirm these facts and to refute was performed.

Bubbles are also very efficient amplifiers of water turbulence pressure fluctuations in the frequency range from a few Hz to 100-200 Hz [18].

3.1. EFFECTS OF THE SEA WATER COMPONENTS ON THE SOUND EMISSION BY A BUBBLE

The effects of salt on the sound radiation were studied using the acoustical characteristics of bubbles released from needles and by breaking waves. Bubble contributions to the ambient noise field of spilling breakers have been studied in laboratory experiments with fresh versus salt water by Kolanyi [9] and the increase in power densities of sound pressure levels in salt water versus fresh water from breaking waves was observed in all frequency range. However in another experiments with the sound pressure level emitted from the cloud generated in salt water by water jet was 3-4 -dB lower comparing with the fresh water.

Sound pressure variations and the change in the damping coefficient of bubbles were observed as the salinity level increased [8]. The observations show that the change in the local surface tension may not alter the acoustic radiation whereas the local influence of the ions on water structure, possibly in a way related to the hydrophobic interactions, may play a dominant role in altering the sound pressure and significantly reducing the quality factor of the bubble sound.

The oscillating bubble behaves as a lightly damped first order oscillator. The emitted signals resemble exponentially decaying sinusoid, with the decay depending on the damped properties of the water-bubble interface and consequently composition and concentration of surface active substances.

Comparing with oceanic water the Baltic sea water has very low salinity, which could affect both bubbles concentrations and the mechanism of sound emission by breaking waves. Also different concentrations of surface active substances could affect time dependence of sound emission by excited bubbles.

3.2. DROP INDUCED BUBBLES AND THEIR NOISE

The drop impacts such as rain, splashes, sprays or breaking waves falling on the sea surface are effective sources of sounds. The radiated noise is associated with three mechanisms of sound generation - the initial impact of drop, oscillations of a bubble in the splash crater (type I bubble) and oscillations of bubbles appearing in the water body 50-80 ms after impact (type II bubble). Sometimes we could observe "delayed microbubbles" generated by tiny particles of aerosols from the corona droplets which appear about 200 ms after the impact - so called III type bubbles. The example of pressure time series during the initial impact of drop and oscillations of gas bubbles, recorded by the Author in laboratory experiments. The data given in the Fig. 1 were sampled with frequency 80 kHz. The data series were filtered in the frequency range 200-30000 Hz in the upper part of the Figure and in the range of 1000-30000 Hz for the bubbles oscillations.

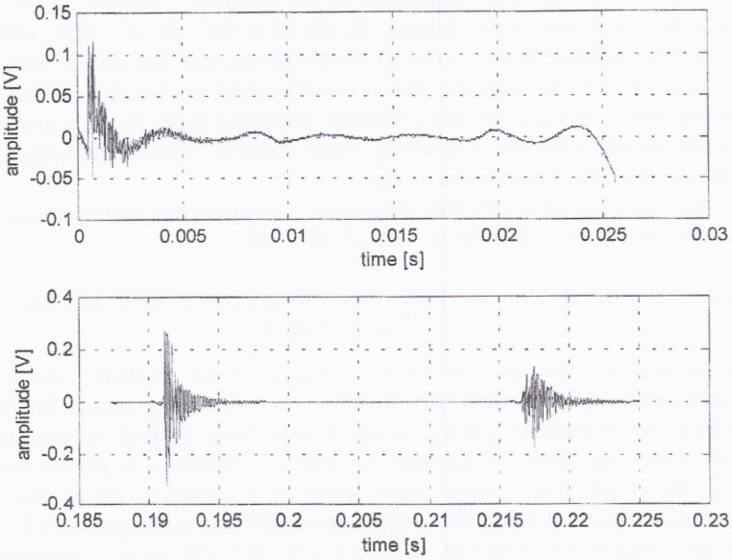

Fig.1. Example of voltage time series registered by hydrophone from impact of droplet (top) on the water coated by surface active substances and oscillations of two low frequency bubbles formed after splashing

Example of acoustical spectra of bubbles oscillation, with sliding window, are presented below in the Fig. 2.

Medwin *et al*. [14] suggested that spectrum analysis of the sound generated by intensive rainfall could be used as measure in estimating the drop size distribution in the rain.

4. NONLINEARITY

It is a commonly known fact that the presence of gas bubbles in liquid causes an effect of nonlinearity in propagating acoustic waves. Since the 1960s, the principle of nonlinearity has been applied for constructing parametric sources. Due to the wide size spectrum of bubbles in the sea water the nonlinear effects are observed in quite a wide range of frequencies. Because of nonlinear behaviour of a bubble driven to high amplitudes, the fraction of incident acoustic energy with frequency f is converted into harmonics and secondary spectral components like $2f, 3f, \ldots, nf$. In case of biharmonic sources we have also difference and sum frequencies $|f_1 - f_2|$ and $|f_1 + f_2|$. The peculiar nonlinearity

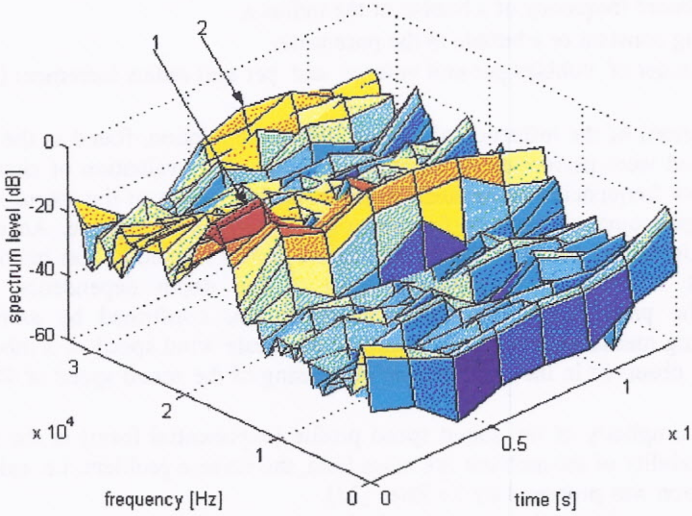

Fig.2. Time evolution of spectral density of the vibrations of two bubbles borned after impact of a water drop on the fresh water surface

properties of bubbly water have given rise to several methods of bubble density estimations. Among those spectral components the sum frequency f_1+f_2 which could be generated only in the bubble medium was used to detect and calculate density of the gas bubbles in the subsurface layer in the Baltic sea by the [6,7]. Another phenomenon - nonlinear response of entire bubble layer was used - instead of the answer of individual bubble, to generate of nonlinear waves at difference frequency [16,17].

In controlled laboratory experiments Orris et al. [18] founded that the most of the acoustic energy emitted during of entering of bubble plumes is broadband and confined to frequencies below 1200 Hz. The excited cloud of bubbles resonate at low frequencies and a spectrum of generated noise much below resonance frequencies of individual bubble. The bubble entrainment is itself a non-linear process. No information about the dependence of the characteristics of emitted by plumes sound on salinity was published.

5. SOUND SPEED DISPERSION AND SUBSURFACE WAVEGUIDE CREATED BY GAS BUBBLES

Contrary to pure water, where sound dispersion is relatively small, bubbly water possesses the high dispersive properties. The frequency dependence of speed of sound in the bubbly water on bubble concentrations could be expressed in the form [1]

$$c(f)=c_0\left\{1-\frac{c_0^2}{2\pi f^2}\int_{a_{\min}}^{a_{\max}} a\, n(a,z)\frac{(f_R/f)^2-1}{\left[(f_R/f)^2-1\right]^2+\delta^2}\,da\right\} \qquad (1)$$

where c_0 - sound speed in bubble free water,
f- frequency of incident wave,
f_R- the resonant frequency of a bubble of the radius a,
δ - damping constant or a bubble in the pure water,
n(a,z) - number of bubbles per unit volume and per unit radius increment (usually 1 μm).

The calculations of the influence of the gas bubble population, found in the Baltic sea, on the sound speed were performed by Szczucka [21,22]. The evaluation of changes of the sound speed at low frequencies in the surficial layer reaches values of the sound speed order of 10 m/s. This phenomenon leads to formation of subsurface waveguide. An exponential form may approximate the ocean-surface sound-speed profile formed by gas bubbles in such waveguide, what reflected an exponential form of the depth dependence of bubble concentration. The presence of this kind waveguide was confirmed by ambient noise observation. During measurements in the nature, at moderate wind speed of 8 m/s, Lamarre and Melville [10] observed in the surface layer decreasing of the sound speed of 400-800 m/s at 5 kHz.

Due to the simplicity of the sound speed profile (exponential form) in the waveguide and the relative stability of the ambient sea noise field, the inverse problem, i.e. calculation of bubble concentration was proposed by Ye Zhen [23].

We should note here, that sound velocimeters working in megahertz range are insensivite to the gas bubbles presence. The sound speed changes caused by the bubbles are also not included in the oceanographic formulae computed the sound speed from salinity, temperature and pressure data.

At low frequencies the bubble dependent refractive surface waveguide shifts the incident angle of the transmitted signals on the sea surface to steeper angles.

6. THE ATTENUATION OF SOUND IN THE OCEAN WATER CONTAINING AIR BUBBLES.

The great difference between the acoustic impedances of gas and water causes the bubble to be effective sound scatterer, especially when insonified at its resonance frequency. At resonance the scattering cross section may be hundreds of times larger than its geometrical size. In consequence, resonant subsurface bubbles in scattering process efficiently attenuate acoustic energy of signals and the bubble layer brings additional attenuation, which increases with frequency [1].

In resonance approximation, for bubble cloud insonified by a harmonic wave of frequency f, the extinction (S_E) and scattering (S_S)cross sections are given by:

$$S_E = \pi c a_o n(a_o)/f \tag{2}$$

$$S_S = 2\pi^2 a_o n(a_o)/\delta \tag{3}$$

where a_0 - is the radius of a bubble in resonance at f.

At frequencies below a few kilohertz the bubble layer at moderate hydrometerogical conditions could be treated as an almost opaque medium for acoustical signals.

The investigations of the influence of the bubble layer on the signals propagation and reverberation under the known Baltic sea conditions, in the geometric approximation, were reported earlier by the Author in [5].

7. SUBSURFACE REVERBERATION

In many cases the sea surface reverberation is a limiting factor in the performance of hydroacoustical systems. For the long period the striking feature of the surface reverberation theory was discrepancy between observed reverberation and the theory of backscattering at rough surfaces. Although the role of gas bubbles in the sea surface screening, emerged in publications of Russian researchers long ago [3], in the western acoustic community this fact was quite long unexplored. The impact of the bubble layer on scattering strength was extensively examined in the late 80s and during the last decade. (review in [11]). For frequencies in the range of 3-60 kHz reverberation is consistent with the view that backscattering due to surface scattering only, at moderate to high grazing angles only. At low grazing angles subsurface reverberation is due to microbubble layer. At low audio frequencies ($f< 1$ kHz) the observed level of reverberation exceeds theoretical ones calculated for rough sea surface. In coastal water reverberation level exceeds values in open water by an order of magnitude. It coincides with the observed higher level of bubble concentrations in coastal waters. The refractive effect caused by the bubble layer sound speed changes, when at low frequencies the bubble layer shifts the incident angle on the surface to steeper angles, explained partly the above mentioned disparities between theory of reverberation and experimental data [4]

Enhancement of the acoustic field due to the trapping effects in the subsurface duct was taken into account by Norton and Novarini [15]. Of fundamental importance is the role that this subsurface bubble layer may play in connection with scattering from a rough air/sea interface. Trough numerical calculations, it was found that the enhancement of the total field is a consequence of scattering at the rough surface in the presence of the upper refracting bubble layer. An enhancement is approximately 40 dB with respect to the bubble-free medium very near the surface for a frequency of 400 Hz, with a grazing angle of 20 deg, and a void fraction at the surface of $3.2 \cdot 10^{-5}$.

The enhancement decreases to about 10-15 dB at 10 m below the surface, but is still significant at depth exceeding the bubbly region. For a smaller void fraction of $3.1 \cdot 10^{-6}$ the enhancement was approximately 5 dB.

8. ACKNOWLEDGEMENTS

The paper has been supported by the Institute of Oceanology PAS, Sopot, Poland.

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