Comparison of the application of linear and nonlinear acoustical methods in the gas bubble counting

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In this work, the application of multifrequency acoustic backscattering method for measurements of bubble population in the sea surface layer and the sea bottom is presented.

Bubbles are driven simultaneously at two relatively close frequencies near their resonance. In the backscattered signal two groups of frequencies are analysed – the two primary ones (f_1 and f_2), and the generated from nonlinear response of a bubble - the sum ($f_1 + f_2$,), doubled ($2f_1$ and $2f_2$) and difference ($|f_1 - f_2|$) frequencies.

The results indicate that using joint analysis at the different group of frequencies in echoes during the bubble counting could be more precise comparing to each of the techniques taking into consideration i.e. linear and nonlinear backscattering used separately.

The suitability and limitations of the setup for bubble density measurements in the ocean environment are considered. Comparisons between the methods show generally agreement in bubble distributions, although values of densities acquired from almost identical volume in a single transmission could differ along the distance from transducers.

Some examples of time series of a bubble concentration received in many-day series of acoustical measurements in the Baltic Sea and in gassy sediments in the Gulf of Gdansk are discussed.

Introduction

There are many branches of the oceanography where information on *in situ* bubble concentration is very important. The bubbles in the subsurface layer are involved in many processes enhancing the gas transfer across the air-water interface (*Woolf, 1993*), influence the sea-air transport of bacteria, salt, heat and electricity.

In hydroacoustics the role of a bubble is enormous. They are recognised as the main source of the ambient sea noise. The dense layers of bubbles in surficial water could change the sound speed values up to hundreds meters per second and strongly affect the sound propagation.

The gassy sediment has different, comparing to the standard one, acoustical properties - as higher attenuation, reflectivity, and lower sound speed. The presence of gases such as methane in the surficial layer of sediments and gas seepage form the dead areas and have unfavourable effects on the seafloor ecosystem. Gases in sediments change their mechanical properties as shear strength and could be potentially a source of blow- outs.

Gas bubbles at resonance, due to the high rate of acoustical scattering cross section to their geometrical dimensions, are quite well recognised using echolocation methods.

Insonified with the high amplitude pressure, bubble volume oscillations become non-linear. This results in appearing integer and noninteger harmonics in signals emitted by an excited bubble (*Zabolotskaya, Soluyan, 1973)*. In some cases it could be hard to recognise the source of harmonics because they might be generated in the measuring setup. The problem could be partly resolved using two-frequency method of bubble excitation. The advantage of the two-frequency method of bubble detection over linear methods is that sum or difference frequencies are generated mostly in the volume where two beams crossed.

The process of generation of the harmonics by bubbles in liquids is well recognised, both in theoretical aspects as experimentally. The size of a resonance bubble in water or in soft muddy sediments can be estimated using the Minnaert resonance formula. But, in case of bubble detection in more consolidated sediments only the form of profiles of nonlinear components could be found.

There is a number of acoustic techniques used to measure bubble concentrations *in situ*. The most simple of these methods are - measurements of linear backscatter at resonance excitation by multifrequency echosounders (e.g. - Nützel, *et al.*, 1994), sound speed measurements, sound attenuation measurements.

Among nonlinear methods employed in sizing bubble population, are:

second harmonic detection (Miller, Williams, Gross, 1984)
nonlinear mixing of low (at resonance) and high frequency signals at a bubble (*f.g.* Newhouse, Shankar, 1984)
combination frequency (Phelbs, Ramble, Leighton, 1997)
difference frequency (Gensano, 1994)
sum frequency (used by the authors, in the Baltic Sea and the North Atlantic area)

In this work, the application of two-frequency acoustic backscattering method for measurements of bubble population in the sea surface layer and the sea bottom is presented.

Theory

The variant of nonlinear method used here to estimate the bubble population is based on the echosounder equation determined for each of linear and nonlinear components -

$$\frac{I_{sc}\{\omega, 2\omega, \omega_1 + \omega_2\}}{I_0} = \frac{\beta\{\omega, 2\omega, \omega_1 + \omega_2\}\Delta V\{\omega, 2\omega, \omega_1 + \omega_2\}}{4\pi R^4} \qquad (1)$$

where -I_{sc}- backscattered intensity for each of the generated component, I_0 - intensity in the incident waves, dV –scattering volume. The scattering volume is different at linear and nonlinear frequencies, and is estimated numerically for different transducer's configurations from predicted beam patterns and their geometry. R - distance from the receiver to the scattering volume, $\beta\{...\}$ - volume backscattering coefficients for different backscattering processes.

The volume backscattering coefficient for each of components is formed as sum of signals radiated by all insonified bubbles -

$$\beta\{...\} = \int \sigma\{...\}\, n(a)\, da \qquad (2)$$

where n(a)da - the bubbles concentration in the unit volume (1 m^3), for a range of diameters of (da=1 μm),

σ - backscattering cross sections.

The volume backscattering coefficient has meaning of the total scattering cross section of the unit volume and is

Into Equation (1) the attenuation of waves propagated in bubble layers or sediments should be included -

$\exp\left(-2\alpha r\right)/r^2$ - forward attenuation at primary frequency,)

$\exp\left(-\alpha_D r\right)/r^2$ - backward propagation attenuation at double/sum/difference frequency.

In mode of estimation of bubbles in sediments also the transmission coefficients at the water-sediments or sediment-sediment boundaries should be also included into Eq. 1.

Knowing the functional dependence between the volume backscattering strength and acoustical cross section of a bubble (Eq. 2) the bubble density $n(a_0)$ is be estimated. After first estimation, the profiles are smoothed and corrected step by step for signal attenuation by the bubbles.

The resonance frequency of bubble embedded in sediments is not so well defined as in the liquid. The research of Anderson and Hampton (Anderson, Hampton, 1994**)** and Hawkins and Bedford (Hawkins, Bedford,1992) indicate that in the simplest case of the spheroid bubble embedded in consolidated sediments have two distinct monopole resonances which are quite different comparing to Minnaert formula. Moreover there are experimental data which show that that bubbles in sediments, especially bigger-sized, looks as disks, tubes or wormholes. In this case similarly to a fish swimbladder many resonances should occur.

Setup

In series of experiments we have used a set of inverted echosounders to sound the sea subsurface layer and sediments. In the most complicated version a planar disk hydrophone with 20-cm-diameter was flanked by six acoustical transducers working as transmitters. The beam of transmitters The transmitters are driven by two channel generator with the acoustical power about 1 kW.

Bubbles are insonified simultaneously at two relatively close frequencies near their resonance with rectangle envelope sinusoidal pulses.

The system usually is lowered from the ship board on a crane up to 10-12 m depth in case of surficial layer investigations. All acoustical beams are looking up or down depending on the goal of experiments.

The echosignals are amplified, digitised at 250-533 kSamples/sec with a 14-bit resolution. In the echosignals from bubbles or gassy sediments after filtration the two group of frequencies are analysed – linear - the two primary frequencies (f_1 and f_2), and generated during nonlinear response of medium - the sum ($f_1 + f_2$,), doubled ($2f_1$ and $2f_2$) and difference ($|f_1 - f_2|$) frequencies.

Because of the ship pitch and roll and the sea surface motion the depth variations of the sensors relative to the surface could be significant. So countermeasures should be applied using the most convenient crane position and software postprocessing. The attenuation of signals going through bubble clouds is additionally estimated step by step on the basis of values echosignals.

For each filtered frequency, signal envelopes are used for parallel estimate of profiles of bubble concentration using the presented above algorithm.

Area of investigation

a) The surface bubble concentration measurements were performed for layer in depths range between 0.5/1 and 6 m and in wind speed range of 0-11 m/s.. The measurements were performed in the spring - summer seasons in the Gulf of Gdansk area, most often at the station P116 with co-ordinates $\lambda = 54^{O}$.40'N, $\varphi = 19^{O}$ 20'S. The wind speed effects on the bubble concentration and depth of entrainment was determined.

b) The sea bottom

The bottom measurements were performed in summer-autumn time. The data were collected at selected points distributed in the inner Gulf of Gulf area where a geophysical or geological survey was earlier performed and documented. (1:200,000 Geological Map of the Baltic Sea Bottom developed at the Branch of Marine Geology for the area of the Polish economic zone) The investigated area includes variety of sediments from hard sand mixed with gravel and till to silt and semiliquid organic origin fluffy sediments.

Generally marine sands of different grain from coarse-grained sand to fine sand cover most shallow water bottom of the Gulf of Gdansk. Muddy sediments cover deep waters of Gdansk Deep. The thickness of muddy sediments on large areas is between 3 and 6 m, locally reaching up 10 m. Water depths at the sampling sites range from 10 to 88 m.

Discussion

a) Surficial layer

In the case of surface layer bubble measurements at low winds indicates that in the results obtained with both methods we could observe disparity, both in values and time dependency, mostly due to linear backscattering at plankton. At higher winds the results converge. It indicate that parallel analysis at the different group of frequencies in echoes during the bubble counting could give less biased results comparing to each of the techniques taking separately into consideration.

b) Sea sediments

The nonlinear method of gas detection in fluid sediments have been found to be excellent instruments for indicating the small bubbles presence in semiliquid sediments.

In case of low attenuating media (mud sediments), the advantage of the sum frequency method comparing to the difference frequency method is clearly visible. For higher frequencies and more attenuated media using the difference frequency is more convenient despite of lower efficiency of generation of difference frequency.

Knowing the absolute values of generated signals and their transmission rate into the sea floor the concentrations of resonant bubbles in the some types of sediments were estimated. In more consolidated layered sediments in was found that bubble could be trapped at the different type sediments boundaries

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