I.N.Didenkulov, S.I.Muyakshin, D.A.Selivanovsky

MEASUREMENT OF BUBBLE DISTRIBUTION IN THE SUBSURFACE SEA LAYER

Institute of Applied Physics RAS
46 Ulyanov str., Nizhny Novgorod, 603950, Russia
Tel: (8312) 38-4282; Fax: (8312) 36-5976
E-mail: din@hydro.appl.sci-nnov.ru

The highly nonlinear response of a bubble to an acoustic excitation makes nonlinear methods possible for bubble observation and sizing. There are various nonlinear acoustic methods of bubble detection. The difference frequency method is described, with application to the bubble concentration measurements in the sea. The results of observations on bubble populations of different sizes with a nonlinear acoustic bubble counter are given. The bubble counter was put in the subsurface ocean layer from the drifting vessel. The unit detected single bubbles of known sizes when they passed through the working volume created by the intersection of high-frequency acoustic beams. Data on bubble concentration are presented and discussed.

1. INTRODUCTION

The subsurface ocean layer is saturated with air bubbles, which play a significant role in underwater acoustics and oceanography. The breaking of surface waves is one of the most likely generating mechanisms, producing bubble clouds in the upper layer. Such bubble clouds influence the gas flux between atmosphere and ocean [1,2], sound propagation and ambient noise generation [3-6].

Many works have been devoted to different acoustic methods of bubble density measurement. They are based on the specific acoustic properties of bubbly liquids. Even the presence of a small number of bubbles can make an enormous change to the sound velocity, attenuation, and scattering, which allows one to realize linear methods of bubble diagnostics [2,7,8].

It is known that a bubble has prominent nonlinear properties. Nonlinear distortions in scattered fields from a bubble are easily observed at the second or higher harmonics of the incident frequency, as well as at the subharmonics of the fundamental frequency and at the sum and the difference frequencies of the primary waves [9,10]. Since a bubble is an oscillator, both linear and nonlinear sound scattering are resonant effects. The existence of such a nonlinear acoustic response opens up the possibility of using it for bubble sizing. The advantage of nonlinear acoustic techniques are their high selectivity. Their usage easily allows one to distinguish a bubble from the other scatterers, since nonlinear scattering from a bubble is much stronger than that from the other scatterers such as solid particles or any other inhomogeneities in fluid. Different nonlinear acoustical methods have been developed for bubble diagnostics: the second harmonic method [11,12], the difference frequency and the sum frequency method [13-15], the modulation method [16], the subharmonic method [17], the subharmonic-modulation method [18-20].

In the present paper we describe ocean measurements of bubble populations made with the use of the difference frequency method. The experimental unit had a small scattering volume and therefore worked as a bubble counter. The unit was deployed into the water from the drifting vessel. The results of measurements of bubble populations in the subsurface ocean layer are presented and discussed.

2. METHOD AND RESULTS OF MEASUREMENTS

The difference frequency method was used for bubble counting. It is based on the insonification of some volume in a liquid (the working volume) with two intersecting acoustic beams of different frequencies. If a bubble appears in the working volume it generates the difference frequency. Since a bubble is an oscillator, the amplitude of the generated difference frequency signal develops through a resonance effect: only resonant bubbles can be detected, since the amplitude of the scattered signal away from the bubble resonance is very small. Therefore, if the detection of bubbles of different sizes is required, one has to use several difference frequencies in a bubble counter. It can be done by keeping the frequency of one of primary acoustic beams constant and then changing the other beam frequency.

The bubble counter consisted of two high-frequency transducers. One of the primary frequencies was kept constant at 1200 kHz, and another was varied step-wise from pulse to pulse as follows: 1160, 1130, 1100, 1060, 1000, 940, and 860 kHz. Correspondingly, the set of difference frequencies was 40, 70, 100, 140, 200, 260, and 340 kHz. Such a variety allowed measurement of bubble size distributions in the range from about 80 to 10 micrometers of bubble radius. Acoustic signals generated by bubbles in the working volume at the difference frequencies were filtered by band-pass filters centred at 40, 70, 100, 140, 200, 260, and 340 kHz. The Q-factors of the filters were about 5. These filters were step-wise switched synchronously with the switching the primary wave frequency. The working volume created by crossing two circular beams can be approximated by a cube with an effective side of about 3 cm, and correspondingly, cross-section area of about 10 cm^2, and volume of 30 cm^3. It was at about 12 cm distance from transducers and from about 10 cm from the receiver. Owing to the relatively small size of the working volume the unit can work as a bubble counter, *i.e.* can detect single bubbles. The bubble counter can also work in a passive regime, *i.e.* when there is no radiation from transducers. In this case the system records acoustic signals in each of the frequency bands of the receiving transducer with the band-pass filters (centred at 40, 70, 100, 140, 200, 260, and 340 kHz). If there is a bubble which is not in oscillatory equilibrium in the vicinity of the receiver, its oscillations generate an acoustic signal centred about the bubble eigenfrequency. Thus, one can obtain a bubble frequency spectrum as mesured by this passive technique.

Measurements were done in the Pacific ocean. The bubble counter was deployed from a research vessel at several depths: 1, 2, 3, 4, 5, and 7 m. Responses from resonant bubbles at each of the difference frequencies were recorded. Responses from the working volume of the device at 1200 kHz were also recorded. Measurements were done mainly from a drifting vessel. The velocity of the vessel relative to the water was measured with a propeller type current meter, which was installed with the bubble counter. This velocity allows one to estimate the bubble concentration. The weather during the measurements was mainly quiet, and varied from absolute calm to wind velocities of up to 8 m/s. Unfortunately, the time for measurements at the vessel was limited and we could not make measurements in a wide range of weather conditions.

The processing of the data was as follows. The number of bubble detection events in the working volume at each of the difference frequencies and at the primary frequency were integrated over the time corresponding to the bubble counter displacement over 10 m relative to the water. This procedure was repeated over a range of conditions (depth, weather). The integrated data corresponding to similar conditions were also averaged to obtain the characteristics of the bubble spatial distribution and bubble frequency spectra.

An example of the spatial distribution of bubbles in a horizontal plane is shown in Figure 1. Data are given for different difference frequencies (upper) and for the linear scattering at the primary frequency 1200 kHz (lower). Shadows in the Figure 1 mark moments of time when the acoustic radiation was turned off.

Bubble frequency spectra were obtained for two cases: when the primary wave transducers were turned on and when they were turned off. In the latter case bubbles appearing in the bubble counter radiated tone-burst signals at their resonance frequencies. These bubbles are naturally excited in contrast to situation when bubbles are excited by two primary waves and radiate signal if their resonance frequencies are equal to the difference frequency.

It is clearly seen from Figure 1 that bubbles are distributed inhomogeneously in the horizontal plane. This is observed at all difference frequencies and the correlation coefficient between the difference frequency channels is about 0.97. Similar very high values were obtained for other measurements. The correlation between nonlinear and linear channels is around 0.85. It is worth noting that such a cloud-like spatial structure of bubble density in the ocean was observed at very small wind velocities. The existence of bubble clouds at medium and high sea states is well known [1]. One may conclude that there is physical mechanism for bubble cloud formation in very different weather conditions in the ocean. It is interesting to estimate from our data the mean spatial interval between bubble clouds. It can be done, evidently, with resolution corresponding to spatial averaging, *i.e*. 10 meters. In particular, for the data in Figure 1 it is about three spatial intervals (30 m). This value was also obtained from other measurements corresponding to wind velocities from 5 to 8 m/s.

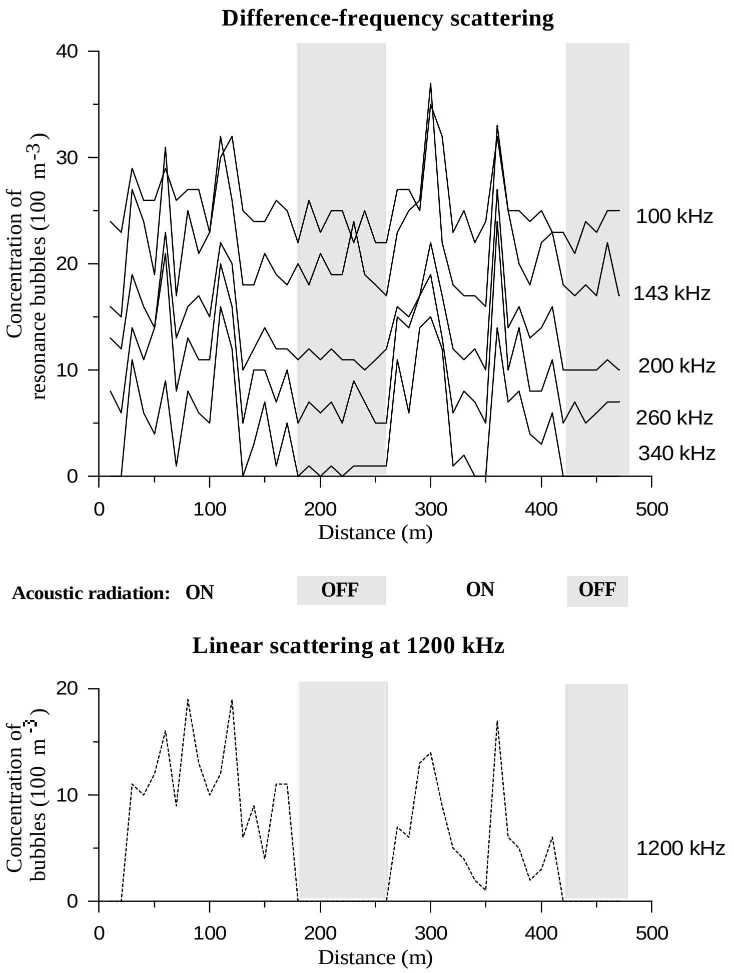

Figure1. Horizontal distribution of the resonance bubble concentration obtained with the bubble counter at 3 m depth by the difference frequency scattering (upper) and the linear scattering at the primary frequency 1200 kHz (lower). Weather: wind velocity 5 m/s, small swell and white caps somewhere. For clarity the curves in the upper figure are vertically off-set from each other by value of 500 m^{-3} (+5 relative to the scale of the vertical axis). Shadows mark moments of time when the acoustic radiation was turned off.

Spectra obtained by the difference frequency method are approximately flat with frequency, while the concentration of naturally excited bubbles decreases with frequency. This can be explained by the higher stability of the form of small bubbles compared to larger ones due to Laplace pressure. Since bubble are recognised as the major source of natural ambient noise in the ocean, this result may be essential to understanding of bubble excitation conditions.

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