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BUBBLE DIAGNOSTICS WITH THE NONLINEAR ACOUSTIC SCATTERING METHOD

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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. Experiments on bubble motion diagnostics in the cavitation water jet are also described.

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] and also play significant roles in sound propagation as well as ambient noise generation [3-6]. Bubbles are also essential elements in many technological processes in industries and in medical diagnostics.

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]. A comparative analysis shows that the sensitivity of the second harmonic method is higher, but selectivity is less compared to the other methods, in particular, to the difference frequency method [12]. The use of the latter in measurements is relatively simple. Some modifications of the method for the case of many bubbles in a scattering volume and for moving bubbly streams have been recently developed [21,22].

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. It allowed one to obtain data on bubble spatial distributions. The results of measurements of bubble populations in the subsurface layer of the Pacific ocean are presented and discussed. It is also described an experiment on diagnostics of bubbly cavitation jet.

1. NONLINEAR ACOUSTIC SCATTERING METHOD

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. The acoustic pressure amplitude of the difference frequency scattered signal at the distance r from the bubble can be expressed as [10,21]

$$P_\Omega = \frac{\sqrt{\pi \sigma_\Omega A_1 A_2}}{2\pi r}, \tag{1}$$

where

$$\sigma_\Omega = \frac{\pi \Omega^4 A_1 A_2}{\rho_0^2 R_0^2 \omega_{1,2}^4 [(\omega_0^2 - \Omega^2)^2 + \delta^2 \Omega^4]} \tag{2}$$

is the nonlinear scattering cross section of a bubble, and where A_1 and A_2 are pressure amplitudes of incident plane waves of frequencies ω_1 and ω_2, respectively, $\Omega = \omega_1 - \omega_2$, where δ is the damping constant, and ω_0 is the bubble resonance frequency:

$$\omega_0 = \frac{1}{R_0}\sqrt{\frac{3\gamma P_0}{\rho_0}}. \tag{3}$$

Here R_0 is an equilibrium bubble radius under static pressure P_0, γ is the specific heat ratio, ρ_0 is the density of liquid. Equation (2) was obtained under assumption $\omega_{1,2} >> \omega_0, \Omega$.

It follows from (2) that only resonant bubbles can be detected: 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.

If a bubble moves the Doppler frequency shift arises at the difference frequency. Supposing that the angles between the wave vectors of two incident waves and the velocity vector $\bar{V}$ of the bubble are ϑ_1 and ϑ_2, respectively and that the scattered wave is received by the transducer 3, whose beam axis is at the angle ϑ_3 to the bubble velocity vector one can obtain the frequency Ω_s of the scattered wave [22]:

$$\Omega_s = \Omega - \frac{V}{c_0}[\omega_1 \cos\vartheta_1 - \omega_2 \cos\vartheta_2 - \Omega\cos\vartheta_3] \ . \tag{4}$$

For the moving bubble the frequency Ω_s must be substituted into (2) instead of the frequency Ω. It is easy to see from (4) that the frequency of the scattered field depends essentially on angles ϑ_1 and ϑ_2 between axes of primary beams and the velocity vector. The Doppler frequency shift at the difference frequency is defined by the frequency shifts produced by two incident waves and the frequency shift produced by the scattered wave. The most interesting case takes place if the angle between primary beams is not small, *i.e.* $\pi/2 \le \vartheta_1 - \vartheta_2 \le 3\pi/2$. Then, the Doppler frequency shift produced by two primary waves are not subtracted each other but added in the receiving wave frequency. Further, the Doppler frequency shift arising from the scatterer motion relatively to the transducer 3 is small if $|\omega_1 - \omega_2| << \omega_{1,2}$. Therefore, the frequency shift at the difference frequency can be very large compared to the linear Doppler frequency shift for frequency Ω and is approximately twice of value of shifts for high frequency primary waves.

High values of the Doppler frequency shift at the difference-frequency scattering opens a way for diagnostics of bubbly streams. Consider the nonlinear difference frequency scattering by an ensemble of bubbles moving with different velocities. Representing of any bubble velocity in the turbulent ensemble as the sum of the regular velocity V_0 (progressive motion of the scattering volume) and the stochastic velocity component $\tilde{V}$ one can find the spectrum of scattered signal as the combination of averaged shift and broadening of the spectrum line. The shift is defined as

$$<\Omega_s> = \Omega - \omega_{1,2}\left(\frac{V_0}{c_0}\right)[\cos\vartheta_1 - \cos\vartheta_2] \ , \tag{5}$$

and the r.m.s. width of the spectral line is derived as

$$<(\Omega_s)^2> = \frac{1}{6}\left(\frac{V'}{c_0}\right)^2\left[4\omega_1^2 \sin(\vartheta/2) + \Omega^2\right] \tag{6}$$

where $\vartheta = \vartheta_1 - \vartheta_2$ is the angle between two primary beams. The Eq.(7) was obtained under supposition that velocities $\tilde{V}$ are statistically independent of bubble sizes and evenly distributed in the entire space angle 4π and in the range of absolute values $(0, V')$. Therefore the analysis of spectra of the difference-frequency scattered signal allows investigation of velocity distribution in the bubbly stream.

2. MEASUREMENT OF THE OCEAN BUBBLE DISTRIBUTION

2.1. Experimental technique

In the experiments we used bubble counters of two kinds. The first one had three primary beams of fixed frequencies oriented in space as a 3D-coordinate system. It allowed one to have three difference frequencies. The working volume of the unit, created by crossing the three beams, was about 15 cm^3. A piezoelectric complex receiver received the scattered signals at difference frequencies and at one of primary wave frequencies. These signals were filtered, amplified and recorded. Transducers generated tone-burst signals with carrier frequencies 1, 1.07 and 1.2 MHz, and consequently the difference frequencies were 70, 130, and 200 kHz. The pressure amplitude in the working volume was about 10^5 Pa. The pulse duration was chosen to be 0.1 ms and the repetition rate was 400 Hz, so that the radiation force on a bubble from the primary acoustic field could not influence the measurements. This bubble counter was used in some preliminary measurements.

The another bubble counter was 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 according to (3) 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 covered by the sensitivities 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 measured by this passive technique.

2.2. Laboratory measurements

The multi-frequency bubble counter was mainly used for measurements of bubble distributions in the subsurface ocean layer. Testing measurements were done in controlled laboratory conditions. Besides testing of the system, laboratory experiments were also aimed at measurement of the bubble damping constant.

Laboratory experiments were done with the bubble counter placed in a water tank. Bubbles in the tank were produced by an electrolysis bubble maker, which was installed under the working volume. The bubble maker consisted of a 30 μm diameter needle. Bubbles of specific sizes were produced by applying an adjusted negative pulse voltage to the needle. Bubbles from the needle rose up and passed the working volume. The radii of individual bubbles were estimated using the Stoke's law by measurement of their rising velocities. In measurements of the damping constant, the bubble counter works in the biharmonical regime, *i.e.* it works at one difference frequency. The pressure amplitudes of the difference frequency signal from rising bubbles passing the working volume were registered. The experimentally obtained dependence of the pressure amplitude from specific bubble resonance frequencies (calculated from their radii) allowed one to estimate the damping constant from the ratio of the effective resonance frequency band Δf_0 to the difference frequency f. An example of such a dependence for the difference frequency 70 kHz is shown in figure 2 as dots. The solid line in the figure represents the theoretical resonance curve with damping factor $\delta=1/6$. For 40 kHz bubbles damping factor was estimated as $\delta=1/7$. Absolute measurements of bubble response amplitudes at difference frequencies shown that amplitudes are satisfactorily described by when these values for damping are substituted into equations (1) and (2). The acoustic pressure amplitude from 70 kHz bubbles at the receiver was about 0.4 Pa.

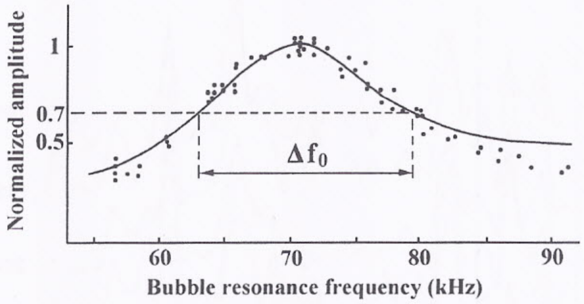

Figure 1. Dependence of the normalized pressure amplitude of bubble response at the difference frequency *f*=70 kHz on bubble resonance frequencies f_0. Dots represent experiment data, solid line is the theoretical curve. Electrolysis bubble resonance frequencies were calculated with the Stoke's law from bubble rising velocities.

2.3. Ocean measurements

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.

One of bubble horizontal distributions is shown in Fig.2. Data are given for different difference frequencies (upper) and for the linear scattering at the primary frequency 1200 kHz (lower). Shadows in the Fig.2 mark moments of time when the acoustic radiation was turned off. Averaged frequency distributions of bubble concentrations at different depths are shown in Fig.3. Data for different depths correspond to the same weather conditions, *i.e.* wind velocity about 7 m/s.

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. Data for these two cases are represented in Figure 4.

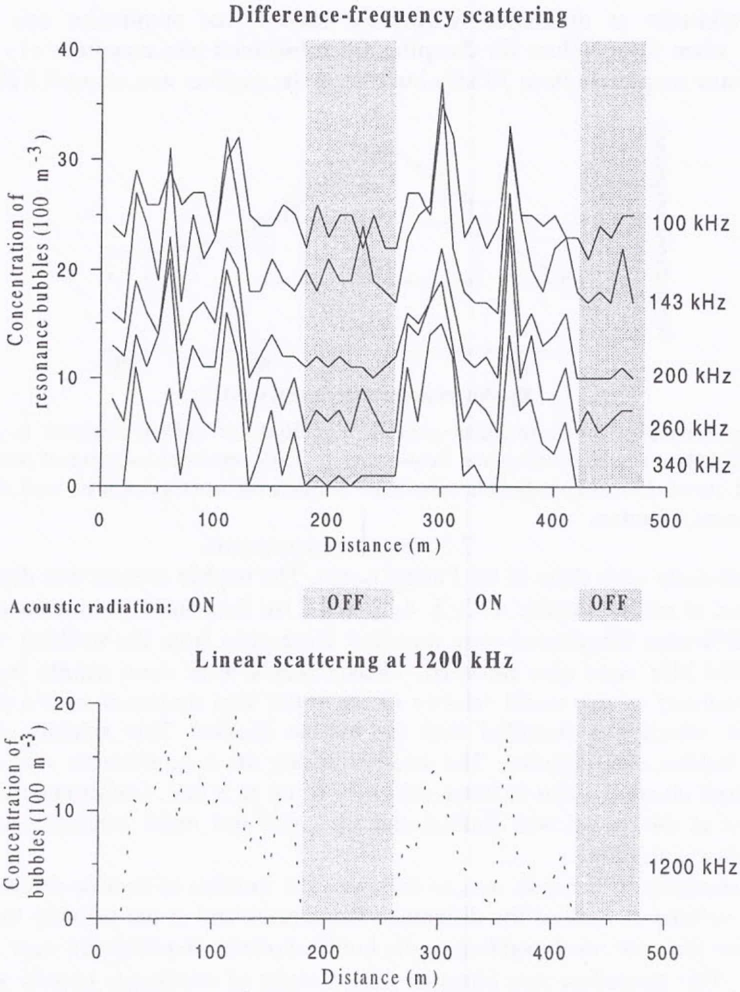

Figure 2. Horizontal distribution of the resonance bubble concentration obtained with the bubble counter at 3 m depth by the difference frequency scattering (upper) and the linear scattering at the primary frequency 1200 kHz (lower). Weather: wind velocity 5 m/s, small swell and white caps somewhere. 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.

It is clearly seen from Fig.2 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 3 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.

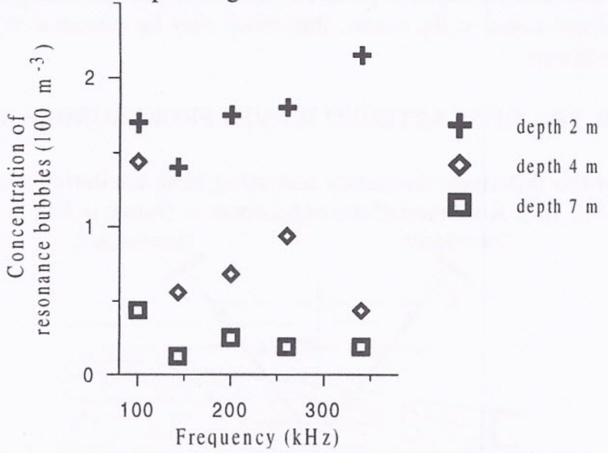

Figure 3. Bubble frequency spectra obtained from different depths. Weather: wind velocity 7 m/s, small swell and white caps somewhere.

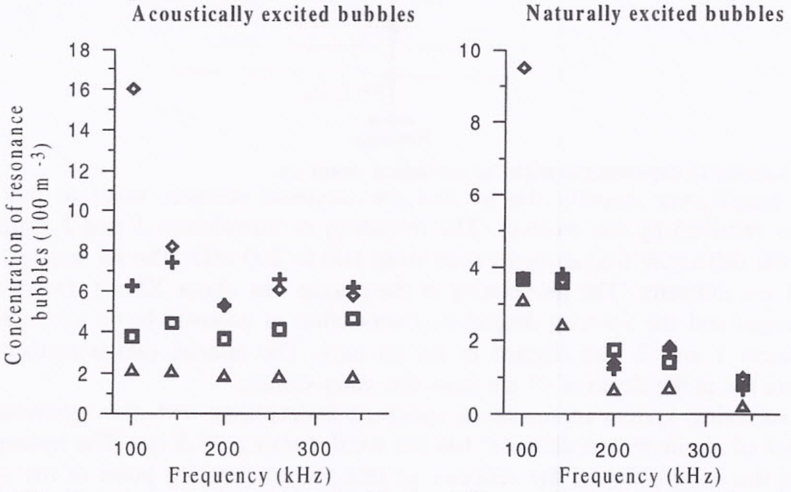

Figure 4. Bubble frequency spectra obtained with the difference frequency scattering method (left) and by passive acoustic recording of sound produced by naturally excited bubbles (right). Data were obtained at the depth of 3 m.

It is known that bubble concentration in the ocean decreases with depth. One class of models describe such a decrease through the use of a single exponent, which is effectively a depth-independent decay length in the vertical direction. Probably a more realistic model consists of a homogeneous upper layer and exponential decay below. The experimentally observed depth dependence shown in Fig.3 better corresponds to the latter model, since the rate of bubble population decrease is essentially higher in the depth interval from 2 to 4 meters than from 4 to 7 meters.

The bubble frequency spectra shown in Fig.4 are interesting. From a comparison of two plots given in the figure, one can see essential differences between acoustically and naturally excited bubbles. 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.

3. SPECTRA OF SCATTERED WAVES FROM BUBBLE STREAM

Investigation of the difference-frequency scattering from cavitation water jet were done in the water tank (3x3x3 m^3). A scheme of the experiment is shown in Fig.5.

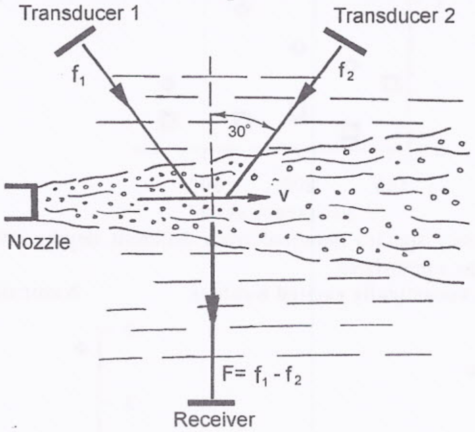

Figure 5. A scheme of experiments with the cavitation water jet.

Two transducers insonify the jet and the scattered acoustic wave at the difference frequency is received by the receiver. The frequency of transducers 1 and 2 were around 1 MHz, and the difference frequencies varied from 100 to 200 kHz. The jet was ejected by the nozzle of 1 cm diameter. The jet velocity at the nozzle was about 20 m/s. Down the stream the jet diverges and the velocity decreases. Intersection of acoustic beam axes generated by the transducers 1 and 2 was aligned at the jet axis. The nozzle, two transducers and the receiver were put at the depth of 41 cm from the water surface.

The receiving system represents a spherical hydrophone with the spherical reflector. The reflector of about 30 cm diameter has the focal distance 27.5 cm. The hydrophone was placed near the focal point of the reflector so that the conjunction point of the system was about the intersection of the incident high-frequency acoustic beams at the jet axis. It allowed one to suppress the reverberation noise in the received signal.

The averaged spectra of received signals at the several difference frequencies were obtained. Measurements of the difference frequency scattering were done at the different distances from the nozzle. The bubble-size spectra changes along the stream: the number of larger bubbles increases down the jet. There is also distribution of bubbles across the jet. Examples of spectra at two difference frequencies are shown in Fig.6.

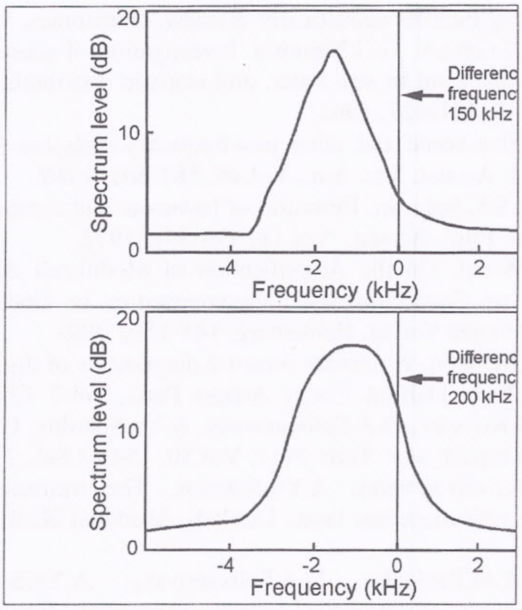

Figure 6. Spectra of acoustic waves scattered by bubbles in the cavitation jet at the difference frequencies 150 kHz (left) and 200 kHz (right).

It is seen from Fig.6 that spectra for the difference frequencies 150 and 200 kHz are different. The mean frequency shift is approximately the same, that corresponds to (5). The form of the spectrum for 150 kHz is sharper than that for 200 kHz, that is related to the bubble-size-velocity distribution in the jet.

4. CONCLUSION

The conducted experiments demonstrate feasibility of the difference-frequency technique for bubble size and velocity spectroscopy, which can find many applications in oceanography, industrial and medical diagnostics. This work was supported by the Russian Foundation for Basic Research (01-02-17653, 00-15-96741, 00-15-96619).

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