PARAMETRIC ACOUSTIC ARRAY IN THE OCEAN: EXPERIMENTS AND APPLICATIONS.

A Sutin

Institute of Applied Physics, Russian Acad. Sci, Nizhny Novgorod, Russia

1. INTRODUCTION

Parametric acoustic arrays (PA) were first proposed in early 60-ies by Westervelt in the USA [1] and Zverev and Kalachev [2] in the USSR . As it is known they are based on demodulation (due to water nonlinearity) of the modulated high-frequency sound beam, which creates in the medium the region of travelling virtual sources, which in turn generates the secondary low - frequency field. Such arrays have unique properties as a wide frequency band, highly directive beam pattern for the relatively small sizes of the pump source, low level of sides lobes. The main disadvantage of PA is the low conversion efficiency.

The idea of the PA is simple - the high directive acoustic emitter radiates simultaneously two high frequency primary waves at frequencies f_1 and f_2 (Fig.1). It is accustomed to call these two waves as pump waves. Because there is a small nonlinearity for the acoustic waves these two primary waves interact one to another. A region of sound interaction serves as a source of waves at combination frequency, and primary, at the sum $(f_1 + f_2)$ and difference $(f_1 - f_2)$ frequencies. It is known that the attenuation of acoustic waves in water depends on frequency and the attenuation distance for high frequency waves is less than for low frequency wave. So the difference frequency wave can propagate on much longer distance the than pump waves and the wave of sum frequency. The interaction volume is bounded in space by the attenuation of pump wave. The difference frequency wave radiates from this volume which can be considered as a virtual end-fire antenna. Each point of this volume is the virtual source of difference frequency wave. The size of the interaction volume is much more than the size of any transducer and it is a reason why the parametric array can provide high directive radiation pattern at the low frequency.

In more common case the pump wave can be modulated wave and the result of the "demodulation" of such wave due to water nonlinearity is the parametric array field.

There are several books [3-5] and many reviews about PA [6-9]. Here the short theoretical description will be given and new experimental results will be presented. This paper is based mainly on the investigations carried out in Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia.

PARAMETRIC ACOUSTIC ARRAY

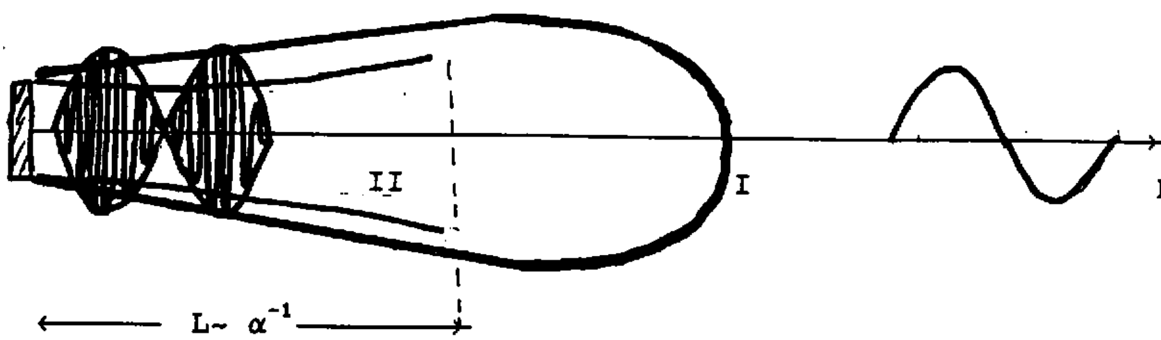

Figure 1. Schematic diagram of parametric array; I - virtual sources volume, II - the directivity diagram of the difference frequency radiation

2. THE ELEMENTS OF THE THEORY

2.1. The basic equations.
The basic equation for description of the PA field is the conventional wave equation having a small additional part due to nonlinearity [3-9]:

$$\Delta p - \frac{\partial^2 p}{c^2 \partial^2 t^2} = -\frac{\epsilon \partial^2 p^2}{\rho c^4 \partial^2 t^2}, \tag{1}$$

where p is the pressure in acoustic wave, c is sound velocity, ϵ is the nonlinearity parameter equal to 3.5 for water, ρ is the medium density.

Owing to the fact that the coefficient of the conversion of intensive primary field to the low-frequency radiation of PA is small, the process of its formation is practically always described in the frames of the given pump approximation. Let a high frequency pump wave be prescribed in the form of a wave beam with time modulated pressure amplitude,

$$p_p = A(\vec{r}, t) cos(\omega t - kx), \tag{2}$$

where A is a slowly varying pressure amplitude, and x is a coordinate along the beam axis. A solution is sought in the form $p = p_s + p_p$, where p_s is a week secondary low-frequency component. Considering p_s to be a slowly varying function, let us average Eq.(1) over a time interval of the order of several pumping periods. Then for the slowly varying component a linear inhomogeneous wave equation results,

$$\Delta p_s - \frac{\partial^2 p_s}{c^2 \partial^2 t^2} = -\frac{\epsilon}{2\rho c^4} \frac{\partial^2 A^2}{\partial^2 t^2}, \tag{3}$$

PARAMETRIC ACOUSTIC ARRAY

The right- hand side of Eq.(3) comprises the distribution of low-frequency field "virtual" sources, associated with the detection of high frequency waves due to the water nonlinearity.

The general solution of the wave Eq.(3) is well known to have the form

$$p_s = -\frac{\epsilon}{8\pi\rho c^4}\int\frac{1}{r}\frac{\partial^2 A^2(t-r/c)}{\partial^2 t^2}dv, \tag{4}$$

Where the integral is taken over the whole volume occupied by virtual sources, and r is a distance from the volume element dv to the observation point.

If the geometry of the pump beam is arbitrary, computing such a three-fold integral even for the case of the free space is a complicated problem. At the same time it is well known that at certain conditions this integral can be considerably simplified and reduced actually to a one-fold one. This may occur in two extreme cases which are used to be called the Westervelt [1] and the Berktay models [10]. These cases depend on the relation between the characteristic scales of the pump wave attenuation L and diffraction R_F which is accustomed to call the Rayleigh length or the far field distance.

$$L \approx \alpha^{-1},$$

$$R_F = \frac{S}{\lambda}$$

Where α is the attenuation coefficient for pump wave, S the square of the pump transducer, λ the wave length of the pump wave.

To compare the attenuation and the Rayleigh distances it is possible to introduce parameter

$$\nu = \frac{\omega\alpha R_F}{\Omega} \tag{5}$$

Where Ω is the characteristic frequency of secondary wave. In the case of bi-frequency pump wave having frequencies ω_1 and ω_2, the low -frequency is difference frequency $\Omega = \omega_1 - \omega_2$. This parameter defines the the condition when one or another model can be valid.

2.2. Westervelt model.

The case was considered in the first paper of Westervelt [1]. This case takes place when $\nu \gg 1$. In the Westervelt paper the more strong restriction was considered - $L \ll R_F$. In this case, the pumping wave appears as a nondiverging but damped beam, with a finite transverse aperture, such that

$$A = A_0 E(\tau) exp(-\alpha x), \tag{6}$$

where $E(\tau)$ is a modulation function, $\tau = t - x/c$, A_0 the pressure amplitude near transducer.

Substitute (6) into (4) and calculate the field in the far-field zone of the beam (at distances $r \gg L$) it is simple to receive the field on PA axis.

PARAMETRIC ACOUSTIC ARRAY

$$p_s = -\frac{\epsilon A_0^2 S}{16\pi\rho c^4 \alpha R}\frac{\partial^2 E^2(t-r/c)}{\partial^2 t^2}, \tag{7}$$

where R is the distance from the pump transducer to the observation point.

In the case of bi-frequency pump wave when the both waves have the same amplitude near transducer A_1

$$E(\tau) = cos(\Omega\tau/2), \tag{8}$$

where

$$A_0 = 2A_1, \Omega = \omega_1 - \omega_2, \omega = (\omega_1 + \omega_2)/2.$$

In this case the integral (4) can be calculated for any direction and the acoustic pressure amplitude for difference frequency wave P_s is defined by formula:

$$P_s = \frac{\epsilon A_1^2 S \Omega^2}{8\pi\rho c^4 \alpha R} D_s(\theta), \tag{9}$$

where θ being the angle between the x-axis and a line directed towards the observation point, $D_s(\theta)$ is the PA directivity diagram having the form

$$D_s(\theta) = \left[1 + \frac{K^2 \sin^4(\theta/2)}{\alpha^2}\right]^{-1/2}, \tag{10}$$

where $K = \Omega/c$ is the wave number for the difference frequency wave.

It is seen that the angular width of the directivity pattern of -3dB level is equal to

$$2\theta_0 = 4\sqrt{\frac{\alpha}{K}}. \tag{11}$$

The Westervelt model was considered for plane pump wave when $\alpha R_F \gg 1$. It is rather simple to show that Eqs.(7), (9) are valid for more weak condition $\nu \gg 1$. In this case the nonlinear interaction take place in the far field zone of the pump waves. Here the pump beam is spherically diverging beam. But in this case the virtual sources may be considered as being in phase within every cross-section of the initial beam in the whole region of interaction. In other words the cross-section of the pump beam is less than that of the first Fresnel zone determined for the low frequency wave. The radius of the Fresnel zone r_F on the distance R from transducer is defined as,

$$r_F = \sqrt{\Lambda R}, \tag{12}$$

where $\Lambda = 2\pi c/\Omega$ is the wavelength of low-frequency radiation. If this radius is much more than the radius of the pump beam all virtual sources in every cross section of interaction region contribute to the secondary field in phase. The radius of the pump beam r_0 can be estimated as

$$r_0 = \frac{\lambda R}{a}, \qquad (13)$$

where a is the transducer radius, $\lambda = 2\pi c/\omega$ the wavelength of the pump wave. From Eqs. (12)(13) it is seen that for distances inside the body of PA ($R < L$) the condition $r_0 \ll r_F$ is equivalent to condition $\nu \gg 1$.

In this case the integral (4) is reduced to a one-fold one along the axial ray of the pump beam and gives the solution (7) (9). Note that the directivity diagram of the secondary radiation under these conditions is considerably wider than that of the initial beam.

2.3. Berktay model

The second case (the Berktay model) usually refers to lower pump frequencies whose divergence is greater and damping less. Here the effect of nonlinear sources front curvature is essential and unlike the Westervelt case the nonlinear sources are not in phase within the whole cross- section of the primary beam. Thus the effective contribution to radiation is given by the secondary sources, whose transverse cross-section is limited by the first Fresnel zone (determined for the low frequency wave) formed around the ray trajectory connecting the emitter center with the point of observation. Herewith the expression (4) is also reduced to the one-fold integral along this trajectory, but the level of the low-frequency field increases much slower with the increase of the interaction length than in the Westervelt regime [1,5] due to essential decrease of virtual sources level because of pump beam divergency. The validity criterion of this approximation is opposite to that of the preceding case: $\nu \ll 1$

The acoustical pressure of difference frequency wave for the Berktay model is given by Eq.:

$$P_s = \frac{\epsilon \Omega R_F^2 A_1^2}{2\rho c^3 R} D_s(\theta) Ei(2\nu), \qquad (14)$$

where

$$Ei(z) = \int_z^\infty \frac{exp(-z)}{z} dz.$$

The directivity diagram of the secondary radiation corresponds here to the square of the diagram of the initial beam

$$D_s(\theta) = D_p^2(\theta)$$

For example below we will consider the the field from the large rectangular radiator operating in parametric regime. The theoretical beam pattern from such PA in the horizontal plane can be described by Eq.:

$$D_s(\theta) = [\frac{\sin(\pi H \sin\theta/\lambda)}{\pi H \sin\theta/\lambda}]^2 \qquad (15)$$

PARAMETRIC ACOUSTIC ARRAY

The intermediate case $\nu \approx 1$ is most difficult to analytical treatment and requires computer calculations. It deserves interest because it is just the case that corresponds to the optimal conditions of PA operation [11]. The important questions is how to determine the optimum frequency of the pump wave. The optimum frequency can be interpreted as the pump frequency at which the field on the axis is a maximum for a fixed radiator diameter. It was established by the computer calculation that the optimal condition take place when $\nu \approx 0.32$. For attenuation law determined by well known formula of Sheehy and Halley the optimal pump frequency is

$$f_{opt} = 19(\frac{F}{a^2})^{2/7}, \tag{16}$$

where F is difference frequency, kHz, and a is the radius of the radiator, m.

2.4. PA efficiency and pump saturation regime.
Let us consider briefly the problem of PA efficiency, i.e. the relation between the power of the secondary wave (W_s) and pump wave (W_p).

$$\gamma = \frac{W_s}{W_p}.$$

The power of the pump wave

$$W_p = A_1^2 S/\rho c.$$

is proportional to the square of the pressure amplitude near transducer A_1^2.
It is seen from Eqs. (9)(14) that the power of secondary wave is proportional to the pressure amplitude to the power four (A_1^4). So the efficiency of the parametric array is proportional to A_1^2, i.e. the pump power. In this sense a powerful PA proves to be most efficient. The efficiency growth connected with the pump power increasing is restricted by nonlinear losses. Such nonlinear losses is a result of a discontinuity formation in the pump beam. The effective length of PA becomes limited to by saturation of the pump wave. The saturation limited PA was considered in the frames of @Westervelt [12,13] and Berktay [14] models. It was shown that in both cases the maximum efficiency of PA is restricted by simple relationship

$$\gamma = \frac{\beta\Omega^2}{\omega^2}$$

where β is a coefficient less than 1, depending on the modulation type. This coefficient $\beta \approx 0.4$ for bi-frequency pump wave.

3. EXPERIMENTS WITH HIGH POWER PA

3.1 The measured parameters of high power PA. The efficiency of parametric array increases with the growth of their power. So the powerful parametric arrays for long range ocean tomography

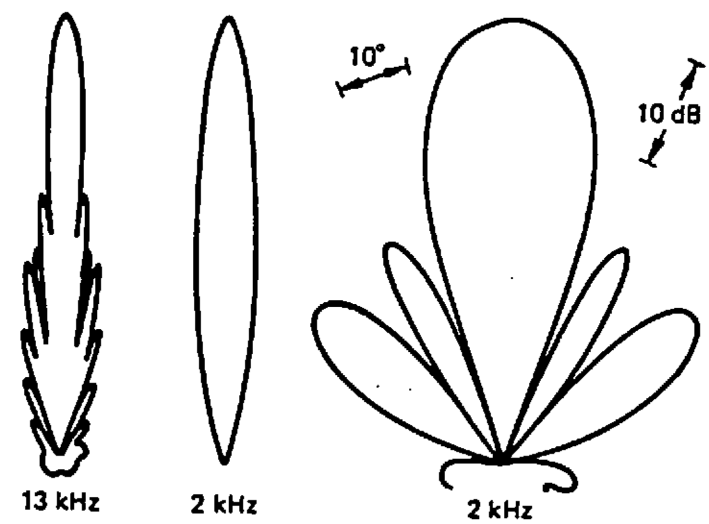

Figure 2. Beam pattern of the USA PA.

have much more efficiency than relatively smaller systems. Such array can be used for long range ocean tomography and for mode selection in the mode tomogtaph of shallow sea. The narrow beam of PA can selective excite modes in the ocean waveguide. The theoretical model describing PA formation in acoustic waveguides was presented in [9,15].

Two high power PA suitable for long range acoustic investigations. The first was developed in the Applied Research laboratories the University of Texas at Austin [7]. A transducer was a circular piston array 2.3 m in diameter, operating at primary frequency in the neighborhood of 12.5 kHz, with the difference frequencies in the neighborhood of 500 Hz to 5 kHz. Total electrical power supplied was 80 kW. The results of radiation pattern measurements are shown in Fig.2.

On the left side of this fiqure is is the pattern for a 13 kHz primary radiation obtained from linear operation of the primary frequency array. Next to this pattern is a 2 kHz difference frequency pattern obtained by driving the system at 12 and 14 kHz and allowing the 2 kHz to be generated in the water through parametric interaction. Notice the narrow the narrow beamwidth as well as the complete absence of minor lobes. The pattern on the right is that obtained from 2 kHz linear emission by the array of conventional low frequency elements. It is seen from center figure that PA has the beamwidth about 4 degrees. These date were taken at a near field range of only 80 m. In the farfield the parametric beamwidth should decrease to approximately 2.5 degrees and remain constant over the 500 Hz to 5 kHz frequency range. Unfortunately we know nothing about any application of this system. According private information this PA had been lost in the sea.

The long range propagation experiments with PA had been carried out in the USSR [16-17]. The

PARAMETRIC ACOUSTIC ARRAY

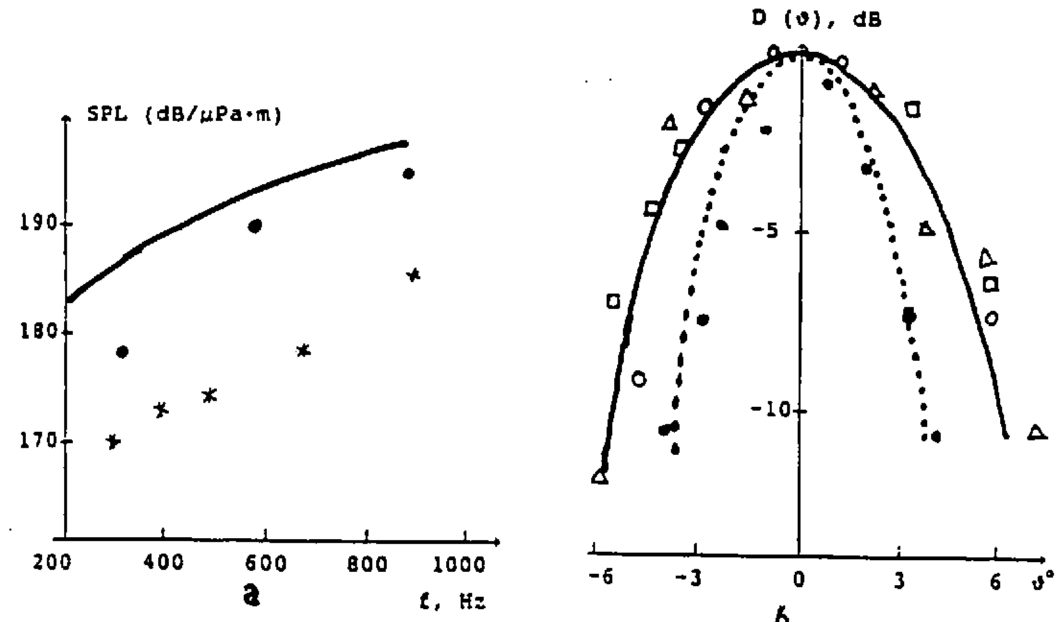

Figure 3. a) Source level of PA extrapolated to 1 m, the measurements at 500m, - the measurements at 2 km. Line is calculated for farfield. b) Beam pattern of the Russian PA. Solid line is theory for excitations of separate halves. Dotted line represent the simultaneous excitation of all source elements by modulated signal. Experimental symbols □ - f=300 Hz, ○ - f=620 Hz, △ - f=970 Hz, • - f=400 Hz.

development of the new PA was rather expensive and the conventional ship hydroacoustic radiator in parametric regime was used. The emitter of the research vessel had aperture 2 x 6 m (the short side being oriented vertically) and was situated under the ship kill at depth about 5 m. In the parametric regime the pump signals of various frequencies of the range 2.9 - 3.9 kHz were sent separately to the right or left halves of the aperture in the first experiments [18]. Later the signals of both primary frequencies were driven separately to different transducer active elements which were alternated on transducer aperture like a net. For the first case the beam pattern width at the -3 dB level was about 7-8 degrees and it was twice less for the second case. To take such directivity by conventional array for the frequency 200 Hz its length must be about 100 m. The total acoustical power applied to the transducer was 24 kW, difference frequency radiation was in the frequency range 200 - 1000 Hz.

The first measurements of the level of the parametric signal were carried out at distances of 600 m to 2 km from the radiator, where the wavequide properties of the channel are not jet manifested, and the free-space equations can be used to estimate the level of the field. Fig. 3 a shows the results of the measurements of the level of the difference frequency field (normalized to 1m) for observation points at various distances. The field of PA was calculated according Eq.(14) obtained from Berktay model.

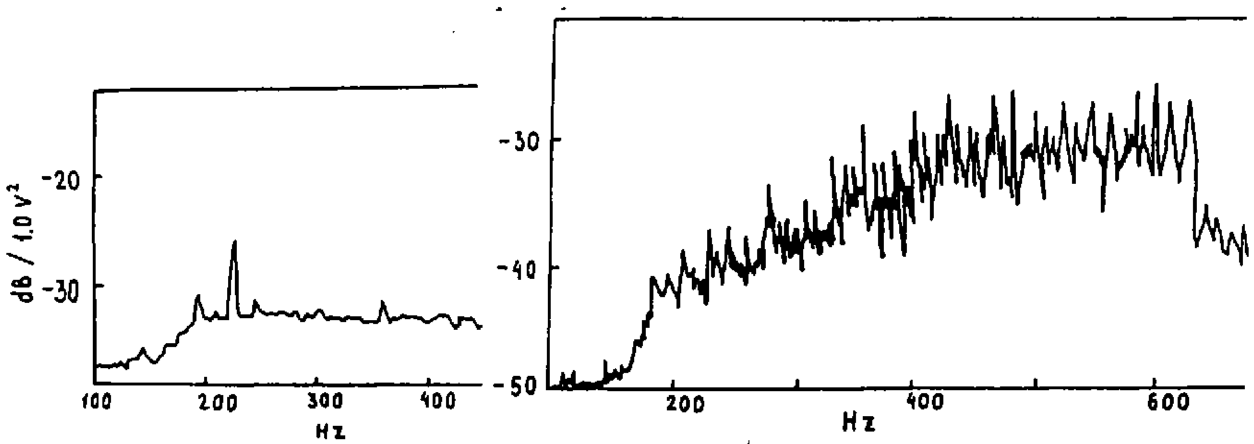

Figure 4. a) Record of signal spectrum received at the frequency 230 Hz at the distance 1000km. b) Record of a FM signal spectrum received at the distance 400 km.

The directivity pattern of PA experimentally measured in the horizontal plane is given in Fig.3 b . It is close to the square of the the square of the pump directivity function, that corresponds to Berktay model of PA. It is seen that theoretical curves obtained from Eq.(15) is rather close to experimental points.

3.2. Experiment on long-range propagation. The most long-range propagation experiments with PA were made in in the Pacific ocean. Acoustic signals were received by a hydroacoustic receiving system located on a shelf close to the beginning of an underwater slope at the depth of about 200 m.

Monochromatic signals of duration 60 and 180 s were radiated at the frequencies 230, 400 and 700 Hz. The regime of frequency-modulated signals radiation was also used when the radiation frequency varied from 230 to 700 Hz during 60 s. The received signals were analyzed using the Bruel & Kjer 2034 spectrum analyzer. Figure 4 a shows an example of the received signal spectrum for the radiation frequency 230 Hz at the distance 1000 km. Frequency resolution was 1 Hz. A marked excess of the signal over the noise (8 dB) is seen here, which proves that reliable reception can be provided at the path several times longer. The spectrum of received FM signal accumulated over the whole realization at the distance 400 km is presented in Fig.4 b.

The use of FM signal enables us to measure the attenuation along the path in a wide frequency band. To determine the attenuation, the envelope of the received signal spectrum was smoothed and averaged over the three received pulses for each point of the path. Figure 5 plots the signal level versus the distance for both the monochromatic and FM signals.

An interesting effect here is an increase of the received signal level at the maximum distance. This increase is due to the excitation of smaller number of modes when transmitter vessel is situated

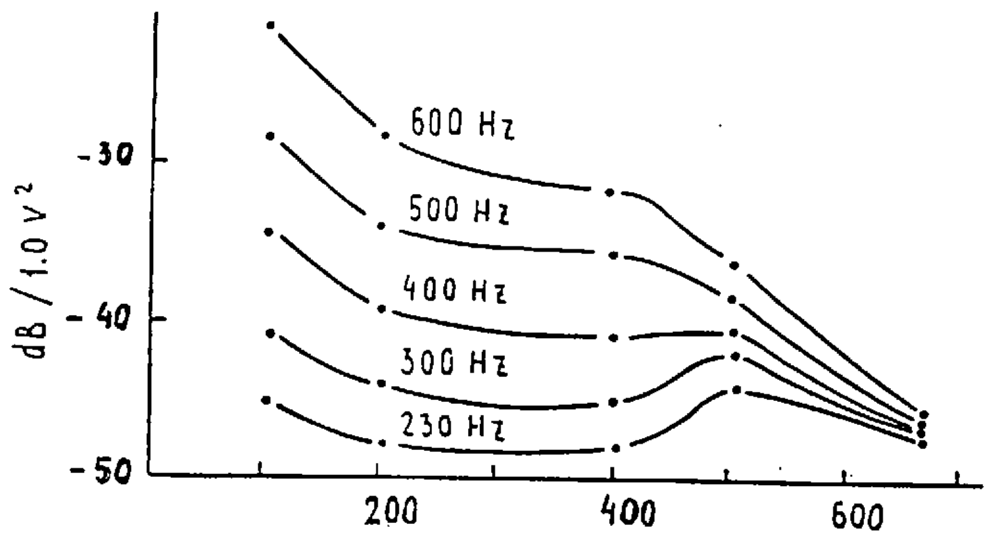

Figure 5. The received signal level as the distance at various radiation frequencies.

in the region of an underwater mountain. Since smaller depth of the channel is penetrated by the sound, the acoustic amplitude increases.

3.3. Experiments in shallow sea

The usage of PA for selective mode excitation in the shallow water waveguide was demonstrated in [8]. The experiments were carried out in in the shallow sea with depth about 320-340 m. The distance between radiated and received vessels was changed up to 22 km. LFM signal with frequency deviation 50 or 100 Hz was used. The convolution of the signal coming to the hydrophone with reference one was performed yielding a number of short pulses passed along various rays or mode groups. Fig.6 show the convolution of the received signal with the mid-band 620 Hz and the deviation 50 Hz correspondently for PA and for the conventional monopole radiator used in control measurements. The distance of observation was 16 km. Comparing the figures one can see that the number of PA radiation pulses and the total length of the pulse train is much less than those for the monopole radiator. Since the total duration of received pulses is defined by the number of the excited waveguide mode , it is clear that PA excites much less waveguide modes than the monopole radiator.

The theoretical interpretation of the observed phenomena were given in [9,19]. The theory was based of a simplified approach. The parameters of the PA in question correspond to the conditions of the applicability of Berktay approximation, and the LF field forms basically before the first reflection of the pump beam from the waveguide boundary, therefore the influence of the boundaries on the PA field formation is not as significant.

3.4. Possible applications of PA for acoustics of shallow sea.

According our opinion, one of the most impotent applications of PA can be connected with low-

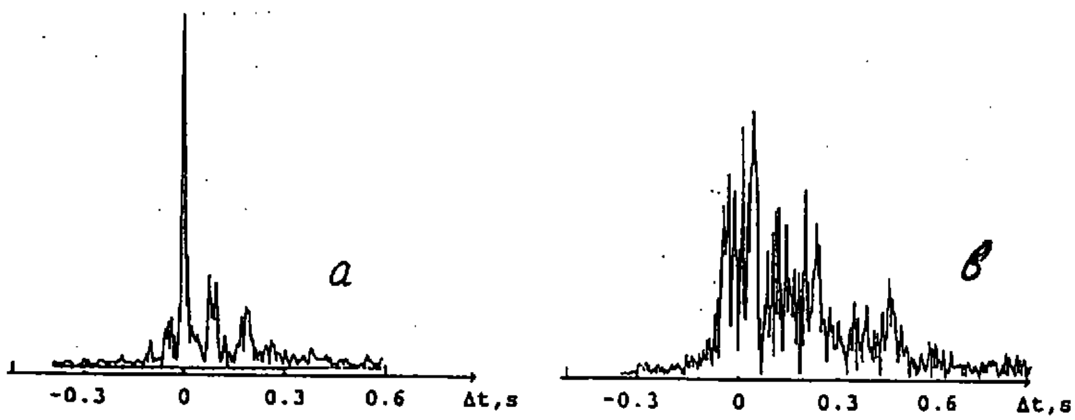

Figure 6. The examples of the LFM signal convolution at the distance 16 km at shallow sea, a - the signal radiated by PA, b - the signal from the monopole source.

mode excitation of the acoustic field in shallow sea. Here parametric arrays can enable new effective methods for investigation of sea bottom and surface, and various inhomogeneities.

As it is known, sound scattering on bottom and surface in shallow sea is the main disturbing factor in the problems of acoustic remote diagnostics. Conventional acoustic systems in shallow waveguides produce multi-mode acoustic fields. This causes strong and nearly unpredictable spatial-temporal variability of the acoustic field; due to the feding signals can become undistinguishable in the background of noise, and the information transmitted along a hydroacoustic channel reduces significantly. Besides there are effects of multi-modal scattering by the bottom and surface roughness what complicates to a larger extent the physical picture.

Significant success in shallow water acoustics may be achieved using low-mode radiation regimes when a single mode or a group of small number of modes with close numbers are excited. Thus, it is highly desirable to work with "mode-selective" sources which are able to excite only one or few modes and , as a result, to simplify the field structure in the waveguide. This is the only way to measure the mode-coupling matrix which is an essential feature necessary to accomplish "scattering tomography", because the environmental information cannot be easily extracted from a point source field which excites a multi-modal acoustic field. A straightforward way to achieve this goal is the use of a vertical array of transducers. However, usually such arrays are costly and have a considerable size and weight (especially if a powerful radiation is needed).

The solution of the problem of the few-mode field formation using PA is just the first step toward the development of methods for remote few-mode sea diagnostics. One can emphasize the following ways to solve the diagnostic problems at present:

- The use of PA for mode-selective excitation will allow to measure attenuation rates for separate modes and, therefore, absorbing properties of the bottom in a broad frequency band (10-1000 Hz). It is also important for the fish characterization, as well as for the inversion of the parameters of intensive internal waves which often have the form of soliton trains in coastal zones.

- Investigation of statistical characteristics of surface waves and of bottom roughness. Elements of normal mode energy scattering (S) matrix become important informative parameters in this case [20,21]. When the Rayleigh parameter is small, the S-matrix elements can be expressed in terms of the spatial spectra of the rough boundaries. Determination of these elements is possible by measuring the energy of scattered modes. Parameters of the secondary modes may be determined by the temporal selection of pulsed signals, or by spatial selection with the help of a vertical receiving array.

- Doppler methods of monitoring of currents, mesoscale eddies and wind waves. Such methods based on Doppler shift measurements of the few-mode signal of PA can provide much higher resolution than those available at present.

4. PA FOR SUB-BOTTOM INVESTIGATIONS

Now the wide application of PA are connected with parametric sonar. Parametric sonars provides new and valuable qualities: decrease in the effects of bottom and surface reverberation, transverse scanning with less interference, high angle and range resolution, the frequency scanning in wide frequency band. The review about such PA applications was given in [7]. Several firms developed such sonars and the most known is ATLAS PARASOUND produced by Krupp Atlas Electronik. It is a parametric echosounder with a very narrow transmission beam for for deep-sea echosounding and for detection of sedimentary layers. The signal can penetrate sedimentary layers to a depth of about 50 meters and to display them in the form of an echogram. The pump frequencies of this PA are (f_2 = 18 kHz) and (f_1 leads in range 20,5 - 23,5 kHz), so difference frequency is from 2,5 to 5,5 kHz. The beam directivity is about 4 degrees. The sound pressure level (SPL) of PA is about 207 dB re μPam, and the SPL of the pump wave is 245 dB re μPam.

Here we consider a new possibility of PA applications for sub-bottom investigations. For such measurements the distances are not so high as mentioned above and the smaller systems are used. For example it is possible to use two separate echo-sounders radiated the signals with different frequencies and the result of interaction is different frequency radiation.

4.1. Coherent enhancement of reflected signals in a parametric echo-sounder.

In the first case we used the simultaneously processing of the pump signal and difference frequency signal to improve the sub-bottom resolution. The high frequency pump signal reflects mostly from a bottom surface and has high signal-to-noise ratio. The low-frequency secondary signal penetrates deeper under the bottom and reflects from sub-bottom layers and buried objects. However the level of these reflected signals is low, often below noise level. In order to enhance the signal-to-noise ratio for these reflected secondary signals, the coherent average technique can be employed with the use of the reflected pump (high frequency) pulses as reference signals. The feasibility of this approach is based on the following considerations: (1) The pump and the secondary signals are always correlated. (2) Average from one pulse to another does not depend on deviation in distance between the transducer and the bottom (due to the pitching, drifting, etc.) because the reference signal (reflected from the bottom pump signal) always follows this deviation. (3) The front of the pump signal is much sharper as compared with the front of the secondary signal. Therefore coherent averaging of the secondary signals can be done precisely. (4) For the "frozen" sub-bottom structure time-delays between the first reflected signal and the all following reflected signals are fixed, therefore the coherent accumulation will take place for all of these signals. The proposed method was proved during feasibility field test performed at Barents Sea. The sub-bottom layer was clear determinate after processing although it was impossible to distinguish this layer from any single reflected signal.

4.2. Nonlinear acoustic methods of the bubble detection at sea and sediments.
The PA was used for bubble measurements in the subsurface layer [22,23]. In such measurements the ability of PA to produce the constant directivity beam in wide frequency band was used. The interaction of the pump waves took place far from bubbles and the measurements was based on linear scattering of PA field by bubbles.

The new remote sensing method of gas bubble layers detection can be based on effect of nonlinear interaction of acoustical wave inside the bubble layer. Since a bubble is a highly nonlinear scatterer, the scattered acoustic fields from a bubble also show highly nonlinear properties. Such scattered fields from a bubble are easily observed at the second or higher harmonics as well as at the fundamental frequency. If two primary acoustic waves of different frequencies are incident on a bubble, the scattered fields at the sum and the difference frequencies of the primary waves also arise. This nonlinear response make the nonlinear diagnostics possible for bubble sizing in the water. The nonlinear parameter of the bubble water can be several order large than nonlinear parameter of the water without bubble. The value of this parameter in water with bubbles can be more than 10^4, although the nonlinear parameter of water is about 3.5. The usage of nonlinear acoustic technique easily allows to distinguish bubbles from the other scatterers since nonlinear scattering from a bubble is much stronger than the other scatterers such as solid particles or any other inhomogeneities in fluid. The review o nonlinear acoustic method of bubble measurements is given in [24]. The results of observation of the nonlinear acoustic effects in subsurface bubble layer by usage of two echosounders working at different frequencies was presented in [25]. Two echo sounders run at 30 and 37 kHz. THe spectral components having sum and difference frequencies in reflected signal was observed. The bubble concentration was estimate from the nonlinear scattering field level.

Here I would like to present the results of usage of nonlinear method for bubble detection in the sea sediment [26]. For such purpose it is possible to use the effect of sum frequency generation.

In our opinion, the usage of two echosounders working at different frequencies, seems to be relevant for detection of nonlinear scattering from gas bearing sediments. For diagnostic purposes, the separation of echosignals at sum frequency is optimal because its amplitude strongly exceeds the difference frequency amplitude. Furthermore, the emission of sum frequency has place in

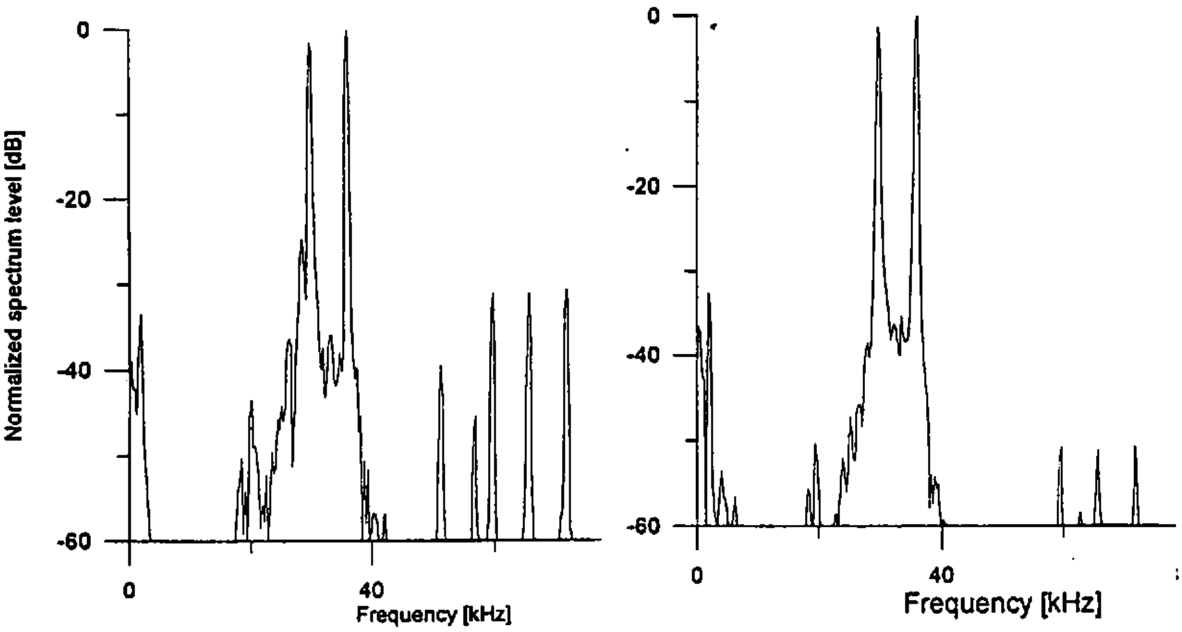

Figure 7. The spectra of the reflected signals from different kinds of bottom : a) organic liquid muds (with gas bubbles), b) medium sand (no gas)

propagation media (with nonlinearity properties) only, when second harmonics components could be generated in power amplifiers or transducers.

The experiment was performed out in the shallow area of southern part of the Baltic sea from the board of rv "Oceania". Two echosounders run at 30 and 35 kHz, each has acoustical about 0.5 kW . Pulse length was 1 ms. The diameters of each of the three transducers (two transmitters and piston type hydrophone) were equal 15 cm. The distance from the transducers to the bottom was the 15 m .

The records of echosignals were performed in different sides of Gdansk Bay where varied known types of the surficial bottom materials present - from an organic liquid muds (probably very rich in gas bubbles) to medium sand (no gas presence was expected). Among the echosignal components, besides the primary frequencies and second harmonics, sum frequency emitted from the gas layer presents. Spectra of echosignals for the contrast type sediments, i.e. mud and sand are shown in Fig.7. It is well seen, that level of the sum frequency component is much higher in the case of mud bottom. It suggest that sum frequency and second harmonic components were generated as bubbles in sediment were driven by two frequency harmonic waves.

The experimental results allow to estimate the gas void fraction in the sea sediments. There were two values of the gas void fraction bubble which corresponds to observed nonlinear scattering. These two concentrations were rather different: the small one was $3 \cdot 10^{-6}$, and another higher concentration was $7 \cdot 10^{-4}$. To determine what concentration is true it is necessary to make additional investigations.

The work was supported by the Russian Fund of Basic Research, grant 95-02-06411-a.

5. REFERENCES

[1] P J WESTERVELT, 'Parametric Acoustic Array', *J.Acoust.Soc.Am*, 35 p535-537 (1963)
[2] V A ZVEREV & A I KALACHEV. USSR Patent Number 5,369,997, Dec 6 (1963)
[3] B K NOVIKOV, O V RUDENKO & V I TIMOSHENKO, *Nonlinear Underwater Acoustics*, American Institute of Physics, USA (1987)
[4] B K NOVIKOV & V I TIMOSHENKO, *Parametric Antennas as Hydrosonars*, Leningrad: Sudostroenie (1990) (in Russian)
[5] R J URICK, *Principles of Underwater Sound*, 3rd Ed. (McGraw-Hill, NY, 1983).
[6] T G MUIR , 'Nonlinear Acoustics and its Application to Sediment Geophysics', *Physics of Sound in Marine Sediments*, Plenum Press. New York-London, (1974)
[7] T G MUIR, L A THOMPSON, L R COX & H G FREY, 'A Low-frequency Parametric Research Tool for Ocean Acoustics', *Bottom-intreacting Ocean Acoustics*, Ed. W A Kuperman & F B Jensen, Plenum Press, New York, , p467-483 (1980).
[8] V A VORONIN, S P TARASOV & V I TIMOSHENKO, 'The Role of Parametric Arrays in the Ocean Research',*Research Trends in Physics: Nonlinear Acoustics*, Ed.K A Naugol'nych & L A Ostrovsky, American Institute of Physics, New York, p231-270 (1994)
[9] V YU ZAITSEV , K A NAUGOL'NYCH , L A OSTROVSKY & A M SUTIN, 'Parametric Acoustic Array in Ocean Waveguides: Theory and Experiment', *Research Trends in Physics: Nonlinear Acoustics*, Ed. K A Naugol'nych & L A Ostrovsky , American Institute of Physics, New York, p190-230 (1994)
[10] H O BERKTAY & D Y LEAHY, ' Farfield Performance of Parametric Transmitters',*J.Acoust.Soc.Am.*, 55 p539-546 (1974)
[11] A M LERNER & A M SUTIN, 'Optimization of Saturation Limited Parametric Radiators', *Sov. Phys. Acoustics*, 34 p390-393 (1988)
[12] A M SUTIN,' Saturation-Limited Operation of a Parametric Radiator',*Sov.Phys.Acoust.*, 24 p55-57 (1978).
[13] J G WILLETE, M B MOFFETT & W L KONRAD, 'Harmonics of the Difference Frequency in the Saturation Limited Parametric Sources',*J.Acoust.Soc.Am.*, 62 p1377-1381 (1977)
[14] S N GURBATOV, I Yu DEMIN & A M SUTIN, 'Interaction of Nonlineariry-Limited Spherical Beams in Parametric Sources', *Sov. Phys. Acoustics*, 25 p294-297 (1979)
[15] L A OSTROVSKY, A M SUTIN & V YU ZAITSEV, ' Parametric Transducing Transmitter in Sea Waveguides', *Frontiers of Nonlinear Acoust.*, Proc.12-th ISNA, Elsevier Science Publishers Ltd, London, p245-250 (1990)
[16] I B ESIPOV, A I KALACHEV, A D SOKOLOV, A M SUTIN & G A SHARONOV, 'Long-range Propagation Experiments with a Powerful Parametric Source',*Acoustical Physics*, 40 , p81-75

(1994)
[17] A I KALACHEV, A D SOKOLOV, G A SHARONOV, A M SUTIN & I B ESIPOV, 'Long-range Sound Propagation from Parametric Array', *Advances in Nonlinear Acoustics*, Ed. H Hobak, World Scientific, Singapore-New Jersey-London-Hohg Kong, p259-263 (1993)
[18] V A ANDEBURA, D M DONSKOY , K A NAUGOLNICH , Yu S STEPANOV & A M SUTIN, 'Sound Field of a Powerful Radiator in a Parametric Regime. *Frontiers of Nonlinear Acoust.*, Proc.12-th ISNA. Elsevier Science Publishers Ltd, Belfast, p229-232 (1990)
[19] D M DONSKOY , K A NAUGOLNICH , A M SUTIN & V YU ZAITSEV, 'Experimental Studies of the Field of a High-power Parametric Radiator in a Shallow Sea',*Acoustical Physics* , 39 p141-145 (1993)
[20 D A ELLIS, 'A Shallow-water Normal Mode Reverberation Model', *J. Acoust. Soc. Amer.*, 97 p2804-2814 (1995)
[21 T C YANG, 'Scattering From Boundary Protuberances and Reverberation Imaging', *J. Acoust. Soc. Am.*, 93 p231-242 (1993)
[22] A AKULICHEV, V BULANOV & S KLENIN S, 'Acoustic probing of gas bubbles in the sea', *Sov.Phys.Acoust*, 32 p.177-180 (1986)
[23] M GENSANE, 'Bubble population measurements with a parametric array', *J.Acoust.Soc.Am.*, 95, 3183-3190 (1994).
[24] L A OSTROVSKY & A M SUTIN , 'Nonlinear Sound Scattering from Subsurface Bubble Layer', *Natural Physical Sources of Underwater Sound, Sea Surface Sound (2)*, Ed. B R Kerman, Kluver Academic Publishers, Dordrecht-Boston-London, p363-370 (1993)
[25] L A OSTROVSKY, Z KLUSEK, A M SUTIN, I A SOUSTOVA, A I MATVEEV & A.I.POTAPOV, 'Observation of nonlinear scattering of acoustical wave in a subsurface bubble layer', *J. Acoust. Soc. Am.*, 98 p2881 (1996)
[26] Z KLUSEK, A M SUTIN, A I MATVEYEV & A I POTAPOV, 'Observation of Nonlinear Scattering of Acoustical Waves at Sea Sediments',*Acoustics Letters*, 1996 (to be published)