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ZVEREV-KALATCHEV PARAMETRIC RECEIVER INTENDED FOR ESTIMATING PARAMETERS OF NONLINEARITY OF THE MEDIUM

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Opportunity of usage of Zverev-Kalatchev parametric acoustic receiver is considered concerning absolute measurements of parameters of nonlinearity of the medium in free acoustic propagation field. Based on Zverev-Kalatchev theory of parametric interaction of acoustic waves there are revealing fundamentals of the inverse parametric measuring system and its typical diagram is presented. It is shown that parameter of nonlinearity of the medium can be measured using geometric and time (phase) parameters even without measuring the absolute force or power characteristics of acoustic fields. Results of experimental measuring of parameter of nonlinearity for sweet water are given.

The structure and theory of operation of the acoustic parametric receive antenna (PRA) has been introduced by V.A.Zverev and A.I.Kalatchev by 1959, further the first demonstration laboratory tests and sea trials have been carried out in 1959-1961 [1,2]. At that time the PRA intended for directional reception of low-frequency signals in water and air has been of the great interest. Consequently, at that time the efforts have been concentrated on PRA having huge size (more than 200 m being erected by Institute of Applied Physics (in 1959-1961 acoustic department of SRRFI) and 340 m by the Texas University ARL, USA). Thus, PRA became the first wide-aperture receive antennas, whereas results of experiments stimulated the practical implementation of infra-low and low frequency range in the underwater acoustics [1]. Nevertheless, low frequency wide-aperture piezoceramic antennas (shipboard, coastal and towed) appeared afterwards as apparently more prospective when applied in tackling to underwater acoustics problems, thus sharply decreasing the interest to PRA as receive antennas [1].

The new interest to PRA has arisen by 70-80s of the 20th century after publication of the complete theory of PRA in [2]. At that time some researches have noted very close concurrence of analytical description of PRA properties and parameters with experimental results obtained in laboratory conditions. These data have allowed developing the proposals on application of PRA as directional measuring hydrophones and microphones [1,3,4].

PRA operated, as the measuring antennas were more successful. Thus, the first parametric measuring hydrophone NPAP-1 designed by V.D.Kalmykov TRTI (now TSUR) by 1979 [3], was followed by parametric medical tomographs, parametric defectoscopes and specialized oceanographic receive systems based on sound-by-sound modulation. This equipment is able to define the parameter of nonlinearity of the medium under action of acoustic field with known amplitude and spectral characteristics, otherwise, to measure the pressure of acoustic fields using known data on the parameter of nonlinearity of the medium in the area of PRA operation.

The above parametric devices can not however determine the absolute values sound pressure level or parameter of nonlinearity of the medium without preliminary absolute measuring of one of these physical quantities, since they both simultaneously define sound-by-sound modulation amplitude [2]. Thus, it is impossible to use the existing PRA as the absolute references neither for the parameter of nonlinearity of the medium nor for sound pressure. However, analysis of operation [2] shows, that at provision of easily checked geometrical requirements and stability of the external low-frequency field, it is possible to conduct measurements of the parameter of nonlinearity of the medium and, accordingly, of sound pressure level without of calibrated reference hydrophones.

Consider the PRA main performances as necessary for definition of absolute values of the parameter of nonlinearity of the medium in free low-frequency (LF) acoustic field. Fig. 1 shows the generalized layout of such measuring PRA.

The PRA consists of the high-frequency (HF) tone electric generator 1, which generates the tone signal running through synchronized switches 2,3 to one of the reverse electroacoustic transducers Tr.A or Tr.B , which, in their turn, radiate the HF acoustic signal into the medium 4 in direction of the other opposite transducer. Here, HF acoustic signal (the signal of a pumping) will interact with the other acoustic fields, thus resulting in its phase modulation according to statements [2]. This modulated signal is received by the opposite transducer (Tr.A or Tr.B, respectively), from which it goes to the HF amplifier 5 through switches 2, 3, then to the phase detector 6 connected to the reference signal source via link 9. Then the signal (LF) picked up by the detector 6 goes to LF band-pass amplifier 7, and further on to the phase modulation level recorder 8.

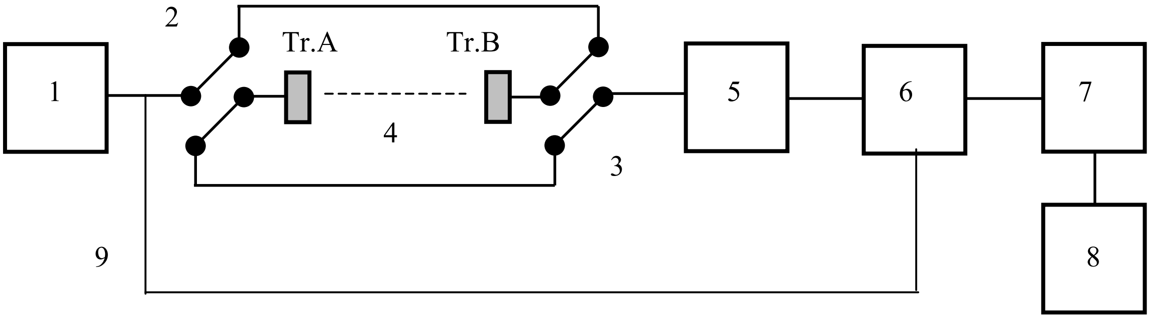

Fig.1

When the propagating external LF acoustic signal having the sound pressure amplitude of P_F at frequency F ($F << f$, f – frequency of pumping HF signal) is acting on the area between Tr. A and Tr. B, then the amplitude of phase modulation φ_0 of the pumping signal will be defined by [2]:

$$\varphi_0 = \frac{\pi f P_F L(\gamma - 1 + 2\cos\Theta)}{\rho_0 c_0^3} \cdot \frac{\sin\left[\pi \frac{L}{\lambda_F}(1-\cos\Theta)\right]}{\pi \frac{L}{\lambda_F}(1-\cos\Theta)}, \tag{1}$$

where γ – is the power of Poisson’s adiabat (for gases) or of Tait’s adiabat (for fluids), c_0 and ρ_0 are sound velocity and density in the unperturbed medium; Θ is the angle between wave vectors of pumping HF signal and LF signal in medium; L is the distance between pumping transducers Tr.A and Tr.B; λ_F is wavelength of acoustic signal of frequency F.

During measurements, PRA consisting of rigidly connected transducers (Tr.A and Tr.B) is located in the medium (Fig.2) which contains free propagating in a far field stabilized LF tonal or tone-pulse signal of frequency F radiated by the external source Pr.F. The stability of amplitude of LF signal is checked by the receiver Rec.F (hydrophone, microphone) located near to receiving PRA base formed by Tr.A – Tr.B at a distance not less than $\lambda_F/2$ behind PRA over the path of propagating of LF signal. The overall dimensions of transducers should be much less L, while the length L of receive PRA should be restricted according to the following requirement:

$$2\pi L < 0{,}8\lambda_F \ , \tag{2}$$

whereas Θ should be in the following limits:

$$0 < \Theta < 60^\circ \ . \tag{3}$$

The measurements are carried out in two stages (Fig. 2). Firstly, HF pumping signal of a frequency f is radiated from Tr.A to Tr.B at fixed radiation of LF signal (angle between HF and LF signals $\Theta_+ = \Theta$), here, phase modulation amplitude φ_+ of HF signal should be measured (Fig. 2a). Secondly, the pumping HF signal of a frequency f is radiated in the reverse direction from Tr.B to Tr.A at the same fixed radiation of LF signal (angle between HF and LF signals $\Theta_- = \pi - \Theta$), here a phase modulation amplitude φ_- of HF signal should be measured (Fig. 2b).

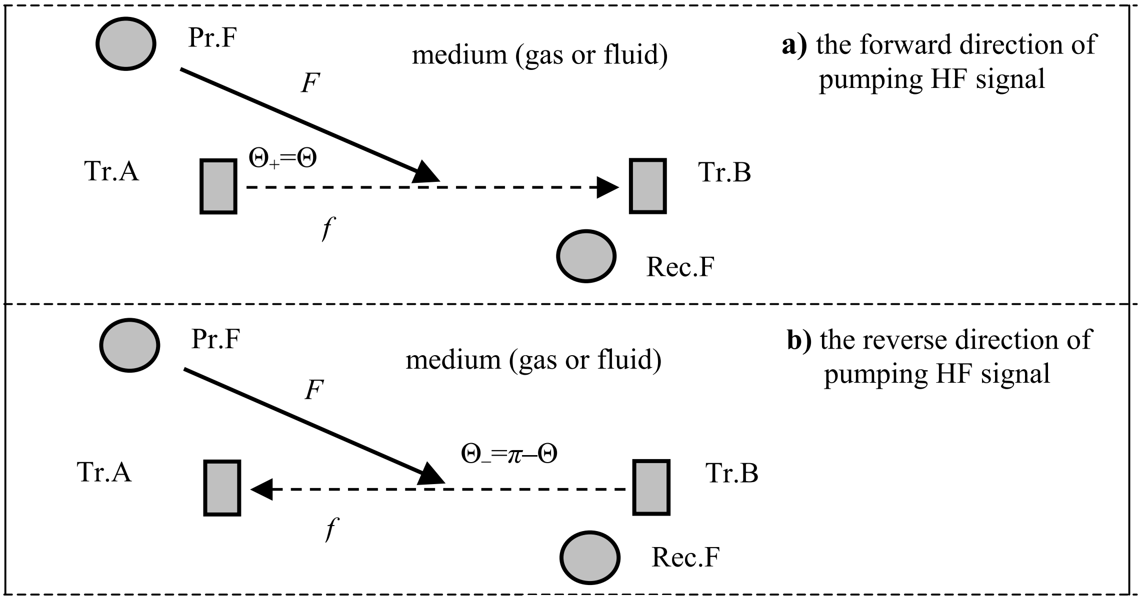

Fig.2

Functional dependencies φ_+ and φ_- taking into account restrictions (2,3) are defined in accordance with (1) using decomposition (1) in a series:

$$\varphi_+ = \frac{\pi f P_F L}{\rho_0 c_0^3}(\gamma - 1 + 2\cos\Theta)\left\{1 - \frac{\pi^2 L^2}{6\lambda_F^2}(1-\cos\Theta)^2\right\}, \tag{4}$$

$$\varphi_- = \frac{\pi f P_F L}{\rho_0 c_0^3}(\gamma - 1 - 2\cos\Theta)\left\{1 - \frac{\pi^2 L^2}{6\lambda_F^2}(1+\cos\Theta)^2\right\}, \tag{5}$$

here, the peak relative error $\delta\varphi/\varphi_+$ of description according to (4) will be less than 0.001 % of the true value φ_+, while the peak relative error $\delta\varphi/\varphi_-$ of description according to (5) will be less than 0.15 % of the true value φ_-. Then, it is possible to go from (4,5) to the equation which describes the power γ only through geometrical Θ, L, λ_F and time (phase) φ_+, φ_- parameters:

$$\frac{\varphi_-}{\varphi_+} = \frac{(\gamma - 1 - 2\cos\Theta)\left\{1 - \frac{\pi^2 L^2}{6\lambda_F^2}(1+\cos\Theta)^2\right\}}{(\gamma - 1 + 2\cos\Theta)\left\{1 - \frac{\pi^2 L^2}{6\lambda_F^2}(1-\cos\Theta)^2\right\}}. \tag{6}$$

Parameters Θ, L, λ_F, φ_+, φ_- included in formula (6) are measured by standard measuring instruments intended for angles, distances, time, and phase detectors as well. Estimation of an exponent degree γ is performed by experimental measuring of Θ, L, λ_F, φ_+, φ_-, substitution of above values in (6) and evaluation of the power γ. Then the parameter of nonlinearity of the medium ε_0 can be defined using the known power γ and formula [5]:

$$\varepsilon_0 = (\gamma + 1)/2 \tag{7}$$

Numerical modeling carried out taking into consideration accuracies of original equations (4,5) and a functional shape of the equation (6) proves that developed reverse method (Fig. 2) is potentially capable of defining values γ: with accuracy 0.5-4 % at $1<\gamma<10$, 4-15 % at $10<\gamma<25$ and 15-60 % at $25<\gamma<50$. At values $\gamma>50$ (is severe nonlinear media) the given method stops operation owing to the growth of the measurement error. Thus, the requirement $\varphi_- /\varphi_+ < (0.95\ldots0.97)$ can be considered as the criterion of applicability of equation (6) for definition γ. Additionally, it should be noted that when PRA operates in gases at $\gamma<2$, then φ_- can take a negative value due to (5), it should be taken into account at definition γ according to reverse scheme (Fig. 2).

Method has been checked in a course of demonstration experiments carried out in the large anechoic basin of The Central Research Institute «Morphyspribor» in 1985-1986. The equipment has been arranged as in the diagram shown in Fig. 2. Then, the NPAP-1 (pumping rate $f = 1$ MHz) was used as a PRA [3], transducers could be switched, the length of receive base L could be selected from 0.4 to 0.6 m with an error of 1 mm, the receive axis of PRA has been fixed in horizon at the depth of 4.5 m. The measuring projector (Pr.F) has been located at a distance 20…25 m from PRA at a depth of 4.5 m. It radiated tone or tone-pulse signals to PRA in a range from 0.1 to 1 kHz (basic measurements were conducted in a range from 0.3 to 0.6 kHz). By the way, the sound pressure of LF field in the area of PRA could be established in limits 1-100 Pa. An angle Θ between the PRA axis and the line formed by Pr.F-PRA could be established from 15° to 30° with accuracy to 0.3°. The main control LF hydrophone Rec.F was placed on the axis Pr.F-PRA (behind PRA) at a distance 1 to 3 m from PRA. The stability of a relative sound pressure level of LF field at given frequency F was constantly monitored by the selective voltmeter connected to a hydrophone Rec.F. All acoustic devices were rigidly fixed in space relating to the basin body. Measurements of sound velocity, frequencies, distances and angles (c_0, F, L, Θ) were carried out by the standard measuring equipment of the experimental basin, the length λ_F has been calculated by $\lambda_F = c_0/F$. Phase modulation levels φ_+, φ_- were measured at the output of NPAP-1. Sweet standing water (settle time in a basin is 1-2 years) with the small additives of chemical salts for suppression (stabilization of water properties) the living activity of seaweed, microorganisms, etc was used as a tested medium.

Experimentally measured parameters φ_+, φ_-, Θ, L, λ_F, were substituted in equation (6), by that the calculation of water γ has been performed. The average value of the power γ for the water (with temperature 15°C) of the experimental basin fixed by experimental results was equal to $\gamma = 7.3$ with accuracy ±0.4, consequently (7), the parameter of nonlinearity of the water in the anechoic basin was equal to $\varepsilon_0 = 4.15 \pm 0.2$.

The studies conducted reveal also the opportunity of development of the sound pressure level reference in the frequency range lower than 1 kHz using the reverse circuit (Figs. 1, 2) under consideration. Really, it is possible to substitute the determined power γ in equation (4) and then to solve the latter in respect of the sound pressure P_F and thus the sound pressure P_F should be defined at a receive axis of PRA simultaneously with γ defined experimentally.

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