COMPLEX INVESTIGATION OF THE FLUCTUATING THERMOHYDRODYNAMIC CHARACTERISTICS OF A MARINE MEDIUM*

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Methods of measuring the fluctuating characteristics of seawater are described. Certain results obtained by using these methods are presented.

The acoustic method is based on using the nonstationary Doppler acoustic effect [1, 2]. Its crux is the origination of an additional phase shift $\Delta\varphi(\tau)$ or the frequency shift $\Delta f(\tau)$ in the elastic vibrations emitted and received relative to fixed source and receiver if the properties of the medium affecting the velocity of acoustic vibrations propagation therein (temperature, salinity, pressure, etc.) vary in time τ.

In particular, the effect also occurs when a medium with constant properties changes the speed and direction of motion relative to an acoustic beam — the acoustic convective Doppler effect.

If some parameter K of the medium under investigation which affects the propagation velocity of the elastic vibrations therein varies with time, a frequency shift occurs proportional to the rate of change of the parameter mentioned:

$$\Delta f(\tau) = f - f_0 = A\frac{dK}{d\tau}, \tag{1}$$

where A is the acoustic constant of the instrument, and f and f_0 are the frequencies of the receiver and source of the elastic vibrations, respectively.

It is expedient to use the frequency method for high rates of change of the medium properties under investigation. In the case of slow space–time fluctuations of these characteristics, it is preferable to record the additional phase shift of the acoustic vibrations, which is proportional to the increment of the parameter being measured:

$$\Delta\varphi(\tau) = 2\pi A \Delta K(\tau), \tag{2}$$

where $\Delta K(\tau)$ is the magnitude of the time change in the parameter. For a simultaneous change in several characteristics, (1) and (2) become, respectively,

$$\Delta f(\tau) = A_1 \sum_{i=1}^{m} \frac{\partial V}{\partial K_i}\,\frac{dK_i}{d\tau}, \tag{3}$$

$$\Delta\varphi(\tau) = 2\pi A_1 \sum_{i=1}^{m} \frac{\partial V}{\partial K_i}\,\Delta K_i(\tau), \tag{4}$$

where A_1 is an acoustic constant; K_i, medium parameter; $\partial V/\partial K_i$ characterizes the change in the velocity of the acoustic vibrations with respect to the parameter K_i; and m, number of parameters varying in time during the measurements.

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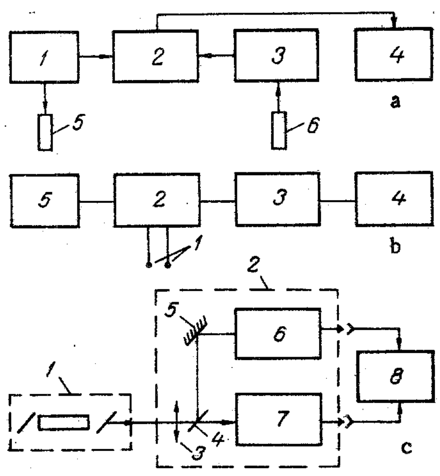

Fig. 1. Block diagram of the measuring apparatus. a) Block diagram of the acoustic channel: 1) electron-counter ChZ-24 frequency meter; 2) Ch7-5 frequency comparator; 3) VZ-14 millivoltmeter; 4) N39 millivoltmeter recorder; 5, 6) ultrasound emitter and receiver. b) Block diagram of the thermocouple channel: 1) copper–Constantan thermocouples; 2) commutator; 3) compensation amplifier; 4) N39 millivoltmeter recorder; 5) null thermostat. c) Block diagram of the optical channel: 1) box with LG-56 laser; 2) box with optical measuring system; 3) cylindrical lens; 4) semiopaque mirror; 5) mirror; 6, 7) PSPR transducers; 8) information-measurement system.

It should be noted that the frequency and phase of harmomic vibrations can be measured with sufficiently high accuracy; hence, frequency–phase methods of investigating the characteristics of media possess high resolution. Moreover, acoustic methods are practically inertialess. Their inertia is determined by the time for the acoustic signal to pass through the section of the medium being checked, which is 10^{-4}-10^{-5} sec under real conditions.

Preliminary computations showed that the phase method possesses a high response to measurements of the physical properties of seawater. Seawater temperature fluctuations can be measured with a sensitivity of $\delta t \sim 10^{-3}$ deg, salinity with $\delta S \sim 10^{-3}$ ‰, and pressure with $\delta P \sim 10^{-2}$ atm, by using the experimental apparatus produced. The volume ultrasonic vibration transducer reacts to a change in all three parameters, i.e., records density fluctuations with a response of $\delta\rho \sim 10^{-3}$ kg/m^3 (we neglect the change in compressibility).

The temperature fluctuations were recorded by a thermocouple compensation method [3]. The crux of this method is that the constant temperature component was canceled, while the variable component was magnified. This afforded a possibility of working with high amplifier gain coefficients and of obtaining good resolution in the temperature fluctuations ($\delta t \sim 10^{-2}$ deg).

The optical method permitted determination of the seawater density gradient, the dispersion of the refractive index, and the anisotropy factor. It is also possible to obtain information about the internal scale of turbulence and the spectrum of the fluctuations in the coefficient of refraction of the medium [4]. The characteristics mentioned were obtained from data on measuring the angle of light beam arrival. A specially constructed position-sensitive photoresistor (PSPR) based on CdS_XSe_{1-X} films was used for this purpose. The PSPR used has a number of advantages [5]: high response at low radiation levels, which affords the possibility of using it in investigations of strongly absorbing media, a broad dynamic range, and low error in the coordinate characteristic.

Full-scale tests of the methods mentioned were conducted in 1976 and 1977 with pinpointing to a buoy and a scientific-research vessel up to 30 m at fixed horizons in the coastal zone of the Sea of Japan. A block diagram of the complex set up is shown in Fig. 1. The quartz oscillator of the electron-counter ChZ-24 frequency meter whose electrical oscillations of 1-MHz frequency were delivered to the ultrasound source and the reference channel of the Ch7-5 device to measure the phase shifts was used as master oscillator of the acoustic channel (Fig. 1a). The attenuated signal went from the ultrasound receiver to the comparison channel of the Ch7-5 device through a wideband amplifier of the VZ-14 millivoltmeter. The phase differences of the acoustic vibrations were measured by a frequency comparator and were recorded by the N39 millivoltmeter recorder. Lead zirconate–titanate piezoceramics were used as electroacoustic transducers. The possibility of studying density fluctuations on a 0.1-1 m base was provided. The whole measuring complex was placed on board the vessel.

Use of the principle of phase amplification of the signals (with subsequent heterodyne conversion and measurement of the phase deviation at the initial frequency) permitted recording phase shifts in the acoustic vibrations up to 10^{-2} deg of angle.

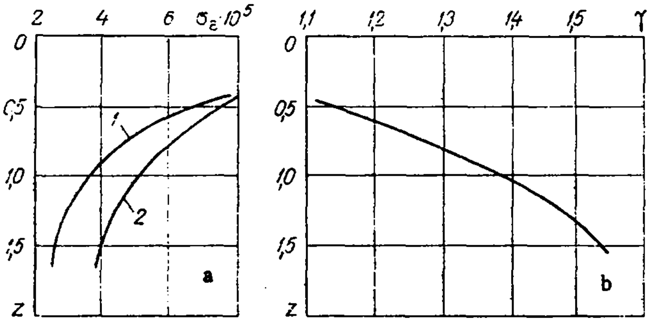

Fig. 2. Results of optical measurements. a) Dependence of the intensity of fluctuations in the angle of optical beam arrival on the depth: 1) parallel to the wave, and 2) perpendicular to the wave. b) Dependence of the anisotropy factor on the depth. z, m; $\sigma_\varepsilon \cdot 10^5$, rad.

Two copper–Constantan thermocouple transducers which measure temperature fluctuations with the time constant ∿0.2 sec were mounted in direct proximity to the ultrasonic-channel converters. The thermal emf from each transducer was fed to the input of an I37 compensation amplifier and hence to the N39 millivoltmeter recorder (Fig. 1b).

The optical apparatus (Fig. 1c) consisted of two sealed boxes with ports located coaxially at 1 m apart. An LG-56 laser with a supply source was in one of the boxes, and the PSPR from the optical system in the other. The PSPR transducer and the laser had adjustment units. The supply and the output signal were transmitted by cable through sealed plugs.

The continuous static information proceeding over the two optical channels in the 0.1 Hz-10 kHz band was processed by a measuring system on board the vessel. To determine the anisotropy factor of the marine-medium density, an optical beam was separated into two in the receiving box and directed to the appropriate transducers oriented in mutually perpendicular planes. The error in recording the intensity of the radiation arrival angle fluctuations did not exceed 8%.

An analysis of the experimental density fluctuation oscillograms indicates the amplitude modulation of the high-frequency density vibrations with a 3-6 sec period, and the low-frequency vibrations with a 1-2 min period. Moreover, still more high-frequency fluctuations with a period less than 3 sec were observed on the oscillograms. Periodicities with such great values of the time (5-8 min and more) were recorded in longer time intervals. The temperature transducers have periodicities of the same order.

Results of the optical measurements are illustrated in Fig. 2. The dependence of the rms value of angle-of-arrival fluctuations σ_ε on the depth of submersion z under slight-waviness conditions (1-2 on the scale) is shown in Fig. 2a. Curve 1 corresponds to a ray being propagated parallel to the wave, and 2 perpendicular to the wave. It is seen that an increase in the depth of submersion results in diminution of the fluctuation intensity. The magnitude of the fluctuations in the coefficient of refraction of the medium can be estimated by using the dependence of the dispersion D_ε of the beam arrival angle fluctuations on the dispersion D_n of the refractive index fluctuations:

$$D_\varepsilon = 4D_n l \pi^{1/2} R^{-1}, \tag{5}$$

where l is the optical base.

Since the radius of correlation during the experiment is R = 0.005 m, then $D_n = 4.08 \cdot 10^{-12}$. Considering the fluctuations in the angle of beam arrival to occur mainly because of temperature inhomogeneities, and using the relationship

$$\frac{dn_0}{dt} = 0.985 \cdot 10^{-4}\ \text{deg}^{-1} \tag{6}$$

(where n_0 is the refractive index and t the temperature of the medium), we obtain that for the rms deviation $\sigma_\varepsilon = 7.6 \cdot 10^{-5}$ rad (the maximum value obtained in the experiments), the corresponding intensity of the medium temperature fluctuations is $\sigma_t = 2 \cdot 10^{-2}$ deg.

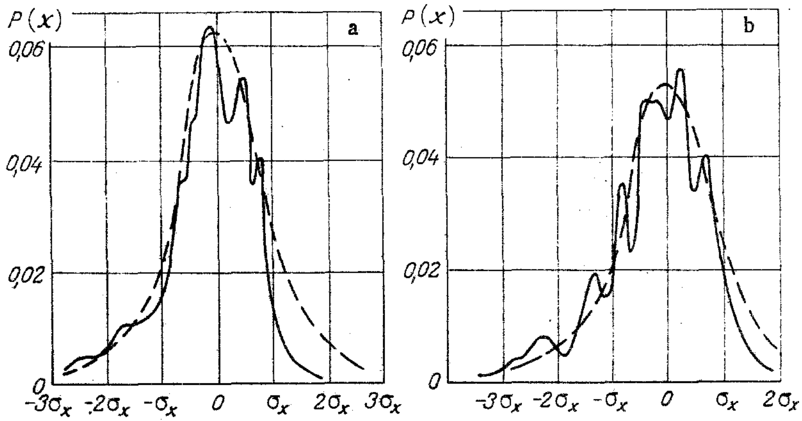

Fig. 3. Distribution law of the seawater density fluctuations for measurements by an acoustic method at the depth 15 m: a) realization time τ = 250 sec; n = 989; m_x = 27.5 mm; D_x = 71.9 mm²; σ_x = 8.43 mm; KM = 0.18; x = 94; b) τ = 600 sec; n = 1746; m_x = 36.7; D_x = 86.4 mm²; σ_x = 9.2 mm; KM = 0.23; x = 36.

The anisotropy factor of seawater was also determined at the depths mentioned. As follows from Fig. 2b, the value of the anisotropy factor grows with the increase in depth. However, it is evident that its growth is possible only to a completely definite depth whose value should depend on the state of the sea surface. In other words, the depth of surface wave propagation can be determined by the kind of dependence of the anisotropy factor γ on the depth z.

Oscillograms of the acoustic measurements were processed on an analog-digital complex including the graph input unit "Siluét" and the electronic computer "Minsk-32," for a statistical analysis of the recorded fluctuations. By using a statistical sample n, the unknown probability density P(x) was determined from random realizations of the density fluctuations $x(\tau)$, then the parameters entering therein (the mathematical expectation m_x, variance D_x, rms deviation σ_x) were estimated, and by using goodness-of-fit tests [6], the validity of the hypothesis advanced was verified. The well-known Kolmogorov (KM) and Pearson or χ^2 criteria were used as goodness-of-fit tests.

The results of processing the most characteristic sections of realizations with different observation times (250 and 600 sec) are presented in Fig. 3, where theoretical (dashed) and experimental (solid curves) distribution laws P(x) of the density fluctuations $x(\tau)$ of seawater are shown and calculated values of the statistical parameters are presented. As is seen from the figures and values of the criteria, the random density-fluctuations processes recorded are almost normal. However, the irregularity of the empirical distribution laws, evidently related to their nonstationarity, shows that the power of the goodness of fit depends strongly on the nature of the deviation of the experimental distributions from the normal distribution, especially at its tails. Thus, 10% deviations in the range $2\sigma_x$–$3\sigma_x$ result in 40–50% changes in the values of the χ^2 goodness of fit.

Presented in Fig. 4 is an experimentally obtained autocorrelation function (solid curve) of the random seawater density fluctuations during a 600-sec observation time. Here an approximate autocorrelation dependence obtained on an electronic computer by using a modified random search method described in [7], whose analytic function has the form

$$R_x(\tau) = D_x e^{-\alpha(\tau)} \cos \beta\tau, \tag{7}$$

is presented (dashed curve), where $\tau = i\Delta\tau$; i = 1, 2, 3, ..., n; $\Delta\tau$ is the discreteness spacing; α and β are parameters characterizing the damping and fluctuation of the correlation function. A rms criterion of the form

$$E(Y) = \sum_{i=1}^{n} [\bar{R}_x(\tau_i) - R(\tau_i, Y)]^2 \tag{8}$$

was used in the approximation, where $\bar{R}_x(\tau_i)$ are the approximated, and $R(\tau_i, Y)$ the approximating correlation functions. This permitted reduction of the problem of approximating the correlation functions to an optimization problem, i.e., to determination of the estimate of the ap-

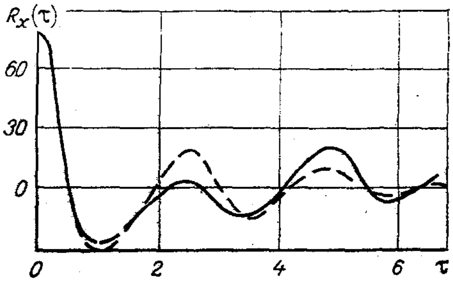

Fig. 4. Autocorrelation function of the seawater density fluctuations for acoustic method measurements at a 15-m depth in 600 sec ($n = 1746$; $m_x = 36.7$ mm; $D_x = 86.4$ mm; $\Delta\tau = 0.15$ sec; $\alpha = 0.4$ sec^{-1}; $\beta = 163$ sec^{-1}; $E = 0.2$).

proximate optimal vector of the parameters Y* from the condition assuring the minimum of the residual E:

$$E(Y^*) = \min_{Y \in \bar{Y}} E(\bar{Y}), \tag{9}$$

where $\bar{Y}$ is the allowable range of the vector $Y = (D_x, \alpha, \beta)$. Optimal values of the parameters for the correlation function are obtained from Fig. 4, $Y^* = (0.86, 0.4, 1.3)$ for $E = 0.21$.

The high-frequency density fluctuations recorded by an acoustic method had periods commensurate with the dependence shown in Fig. 4. For instance, it can be noted that $\alpha \approx 2/T_m$, $\beta \approx 2\pi/T_m$, $\tau_{cor} = (1\text{-}3)/\alpha$ [8], where T_m is the mean fluctuation period, equal to 2-5 sec, and τ_{cor} is the correlation factor of the fluctuation components.

Therefore, the correlation analysis and machine methods of optimization permit clarifying the latent periodicity of the fluctuation characteristics of seawater, and refining their parameters.

Therefore, a comparison of the measurement results for the acoustic, optical, and thermal contact methods showed that the seawater density fluctuations occurred at given horizons mainly because of temperature fluctuations. The influence of the remaining perturbing factors (salinity, pressure) under slight-waviness conditions is not felt. The amplitude of the high-frequency temperature fluctuations with the 3-6 sec period was 0.01-0.03 deg, and the amplitude for the lower-frequency fluctuations with the 1-2 min period was 0.3-0.5 deg. Moreover, temperature fluctuations with period less than 3 sec, whose amplitude was on the order of 0.001 deg, were recorded by acoustic and optical methods.

As the results of machine processing of the measurements showed, the high-frequency fluctuations are a result of a slight turbulent background, while the low-frequency fluctuations are caused by short-period internal waves of quasisinusoidal shape [9, 10]. The appearance of groups of internal waves localized in space and time was apparently recorded during the measurements.

Acoustic and optical nondestructive methods, described in this paper, permit the study of a finer structure and fluctuation of physical seawater parameters because of their high response and low inertia (micro- and macroscales, spectral composition, etc.) and investigation of surface and deep current dynamics and surface and internal waves. The compensation thermocouple method can be used successfully to investigate the long-time temperature series at different depths.

An automated multichannel marine geophysical probe to investigate the thermohydrodynamic characteristics of seawater, which was tested in the expedition, is being produced at the present time in the Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR, on the basis of the methods described.

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GENERALIZED FORM OF THE EQUATION OF STATE OF REAL GASES

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A simple and reliable equation of state is proposed on the basis of an analysis of the geometric structure of the thermodynamic surface. A three-parameter procedure for generalizing the properties of a wide range of nonpolar gases is validated.

One of the most important conditions for the successful use of the theory of thermodynamic similarity to calculate properties of little-studied gases is the existence of a physically sound equation of state common to the materials being considered which has a form giving the correct configuration of thermodynamic surfaces in the range of parameters being investigated.

To construct the equation of state corresponding to the condition indicated above we investigated the thermodynamic surfaces of a large number of technically important gases. The equation of the state surface can be written in the general form

$$X = X_0(T) + \Delta X(T, \rho), \tag{1}$$

where $X_0(T)$ is the ideal-gas component of the property X and $\Delta X(T, \rho)$ is a function which takes account of the difference between the properties of the real and ideal gas. The latter can be written in the form of a virial series. Then when $X = \rho V$, Eq. (1) has the form

$$pV = RT + RTB\rho + RTC\rho^2 + \ldots . \tag{2}$$

Lines on the state surface along which the properties of a real gas coincide with those of an ideal gas at those same temperatures are called ideal curves. These include curves of minima on isotherms of various properties $(\partial\Delta X/\partial\rho)_T = 0$ (Boyle, inversion, Joule curves), ideal curves $\Delta X = 0$ (curves of an ideal gas, ideal enthalpy, ideal internal energy).

In spite of the different meaning which is commonly inserted into the definitions of these properties (thermal, caloric) they have a number of common, not always obvious, regularities which are manifested only in the combined processing of experimental data. We have noted [2] that the ideal curves $\Delta pV = 0$, $\Delta H = 0$, $\Delta U = 0$ in the coordinates (T, ρ) are isomorphic, i.e., they are characterized by the repetition of configurations; the same applies to the curves $(\partial\Delta pV/\partial\rho)_T = 0$, $(\partial\Delta H/\partial\rho)_T = 0$, and $(\partial\Delta U/\partial\rho)_T = 0$. In addition, ideal curves of various properties are connected by thermodynamic relations which result from the coincidence of the lines $\Delta pV = 0$ and $(\partial\Delta F/\partial\rho)_T = 0$, $(\partial\Delta pV/\partial T)_\rho = 0$ and $(\partial\Delta U/\partial\rho)_T = 0$, $(\partial\Delta H/\partial\rho)_T = 0$ and $(\partial\Delta pV/\partial T)_p = 0$. In addition, it should be noted that the ideal curves $\Delta X = 0$ are rectilinear in the coordinates T, ρ, and when extended to $T = 0$ intersect at the common density ρ_0 [1], which as shown by one of the authors [10] can be identified with the density of the ideal unstressed crystal at 0°K. And finally, the most important fact: the curves $\Delta pV = 0$, $\Delta H = 0$, $\Delta U = 0$ belong to the extensive family of curves which satisfy the condition [1]

$$\frac{\partial}{\partial T}[\Delta pV \cdot T^n]_\rho = 0, \tag{3}$$

or

$$\frac{1}{n}\left(\frac{\partial\Delta pV}{\partial T}\right)_\rho = -\frac{\Delta pV}{T}, \tag{4}$$

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