10. A. A. Andronov, E. A. Leontovich, I. I. Gordon, and A. G. Maier, Qualitative Theory of Second-Order Dynamic Systems, Nauka, Moscow (1966).
11. Yu. A. Buevich and V. V. Butkov, "Random pulsations in a coarsely dispersed fluidized bed," Inzh. Fiz. Zh., 35, No. 6, 1089-1097 (1978).

MEASUREMENT OF THE STATISTICAL CHARACTERISTICS OF A TURBULENT BOUNDARY LAYER IN A NATURAL ENVIRONMENT

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Certain characteristics of a turbulent boundary layer are measured in a natural setting by means of an automated measurement system. Deviations of the investigated process from the Gaussian description are inferred on the basis of measurements of the higher statistical moments.

The work reported here was carried out as part of ebb-and-flow tidal studies during February-May, 1980. The measurements were performed at depths less than or equal to 100 m. The experimental test site was a level area of sufficiently large extent with a slightly varying diurnal current. The mean temperature at such shallow depths is determined mainly by solar radiation and heat transfer between the surface of the ocean and the atmosphere. The diurnal temperature variation falls within 1.5-2°C. The temperature drops at depths to 100 m do not exceed 0.1-0.3°C.

The salinity at the indicated depths varies within 2-3% limits. A maximum occurs at roughly 50 m. Diurnal variations were not observed. It can therefore be concluded that the salinity is virtually unaffected by the temperature in the top surface layer of the ocean. The majority of the Soviet and foreign measurement systems designed for the investigation of oceans and inland seas record the average parameters of the ocean medium. However, from the point of view of predicting and observing such phenomena as hurricanes, typhoons, tsunamis, etc., it is exceedingly important to understand the formation and evolution of small- and large-scale oceanic structures.

The AIK-1 measurement system includes primary sensors with capabilities for local measurements of the mean values of the velocity, temperature, and electrical conductivity as well as velocity and temperature fluctuations. The system can also be used for statistical processing of the experimental data in the real-time and data-storage modes.

A prototype model of the AIK-1 system was built by the Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR and the State University in Donetsk.

The AIK-1 automated measurement system is designed to record signals proportional to the local average hydrothermodynamic and small-scale fluctuations characteristics of the ocean medium at depths to 200 m, convert those signals into digital code, and enter the latter into a D3-28 minicomputer for on-line statistical processing and storage.

The following units are included in the automated measurement system:

a) a temperature-compensating hot-wire anemometer HA and resistance thermometer RT for simultaneously measuring the instantaneous values of the velocity and temperature fields in nonisothermal flow;

b) a conduction anemometer CA for measuring velocity fluctuations in a local volume of a slightly conducting fluid flow;

c) an electrical conductivity meter ECM for measuring the average value of the electrical conductivity;

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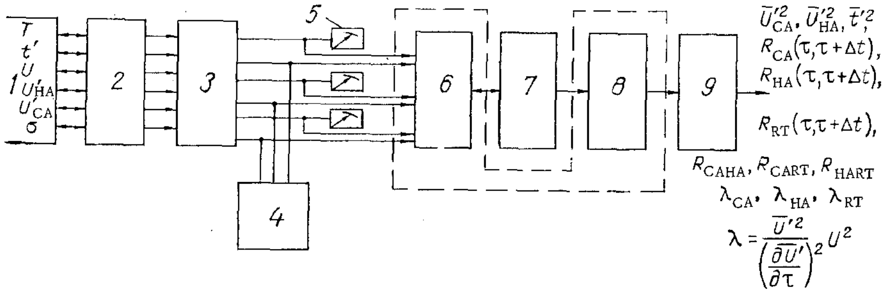

Fig. 1. Block diagram of the AIK-1 system: 1) ocean medium; 2) submersible assembly of primary sensors; 3) shipboard instrumentation assembly; 4) autoplotter; 5) voltmeters; 6) switching unit; 7) ADC; 8) computer interface/input device; 9) D3-28 minicomputer.

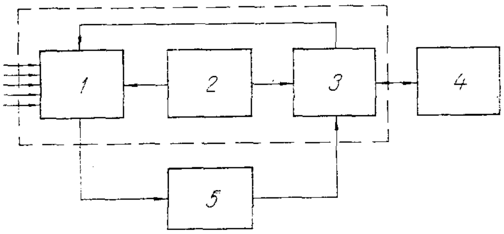

Fig. 2. Six-channel interface/input device for the minicomputer (block diagram): 1) analog switching unit; 2) power supply; 3) potential-reduction printed-circuit board; 3) D3-28 minicomputer; 5) ADC.

d) a standard F733/1 11-place voltage-to-code converter;

e) a six-channel interface/input device for use in conjunction with the D3-28 minicomputer.

Technical Specifications of the System

Range of measurable mean velocities	0.1-2 m/sec
Dynamic range of hot-wire anemometer HA	50 dB
Range of measurable mean temperatures	−2-30°C
Dynamic range of resistance thermometer RT	40 dB
Mean-temperature sensitivity	0.05°C
Range of measurable mean values of the electrical conductivity	1.5-6.5 S/m
Threshold sensitivity of electrical conductivity meter ECM	0.002 S/m
HA frequency range for measurement of velocity fluctuations	0.02-400 Hz
Calculated velocity-fluctuation sensitivity of HA	10^{-3} m/sec
CA frequency range for measurement of velocity fluctuations	0.5-400 Hz
CA velocity-fluctuation measurement range	$4 \cdot 10^{-3}$-1 m/sec
Frequency range for measurement of temperature fluctuations	0.02-400 Hz
Temperature-fluctuation sensitivity	0.005°C

The system is structurally divided into two sections: a submersible probe and shipboard instrumentation. The submersible probe comprises a metal structure, to which are rigidly attached air- and watertight cylindrical metal containers. One end of each cylinder accepts the sensing element of the measuring device. The containers house electronics for extraction and amplification of the useful signals. These signals are then transmitted by shielded cables to the shipboard instrumentation system for processing. The carrier structure of the submersible probe has special equipment for aligning the sensors with the flow.

The shipboard subsystem records and processes the incoming experimental data. The recording operations are performed by dial-indicator and digital voltmeters and by an N327-3 three-channel autoplotting millivoltmeter. The values of the statistical characteristics are read out after data processing on the display panel of the D3-28 minicomputer (digital printout is also possible on a Konsul-254 printer or a PL-150 perforator). The magnetic tape unit of the D3-28 computer is used to store experimental data in digital form. A block diagram of the system is shown in Fig. 1. The general principles utilized in the design of the primary instrumentation are well known from the literature [1].

The six-channel interface/input device for the minicomputer is designed for the sequential switching of analog signals from the shipboard instrumentation to an analog-to-digital converter (ADC), reduction of the output potentials of the ADC to the input voltage level of the minicomputer, and the control of data input to the computer.

A block diagram of this device is shown in Fig. 2 (enclosed in dashed lines). The device operates as follows: On an instruction from the computer the analog signal from the first channel of the switching unit is sent to the ADC input, and the ADC output signal, converted into binary code, is sent to the potential-reduction circuit board, where the ADC output potential of 0-6 V is reduced to the minicomputer input level of 0-5 V. Then on a sync pulse from the computer the 11-place binary converted code is written in the internal storage unit of the computer. Depending on the processing software of the computer, either programmed operations are performed on the number obtained, or it is stored. After completion of the operation the computer generates a switching signal, followed by a signal to trigger the ADC, and the process is repeated. In this manner all six channels are interrogated and stored. This device permits each channel to be interrogated at a frequency up to 1.3 kHz in any sequence. In hardware terms the device is made in the form of a single unit with circuit boards arranged in it for padding, voltage reduction, and stabilization. The switching unit is a K590KN1 microcircuit, the padding device comprises series 554 microcircuits, and the voltage stabilizers incorporate 142EN1A microcircuits and 701MP23 modules. Power is supplied by the shipboard 220-V line.

The submersible part of the system was planted firmly on the bottom at various distances from the base. Prior to some measurements at comparatively large distances from the base, the instrument assembly was endowed with zero buoyancy, and a series of measures were taken to eliminate the effects of vessel drift and periodic disturbances. Before the signals proportional to the velocity and temperature fluctuations were subjected to statistical processing on the computer, they were visually analyzed, and a special program was used to set the sampling time.

In order to record the experimental data and subject it to statistical processing in the minicomputer it was necessary to develop a large package of programs, which was stored on magnetic tape in a unit with a capacity of 16128 steps. The recorded data are replicated fivefold, and the validity of readout from the tape unit is verified by a summation check. The program package consists of a main program and a set of subroutines. The main program controls the switching unit, determines the sampling frequency (timer), and organizes the calling of subroutines and their subsequent loading into internal storage. Each subroutine is designed for the computation of one or more statistical parameters; at most 63 subroutines can be activated concurrently.

The processing programs can be nominally divided into four groups: 1) test program to monitor the performance level of the system; 2) real-time data processing program; 3) program for writing on tape; 4) program for the processing of data stored on tape.

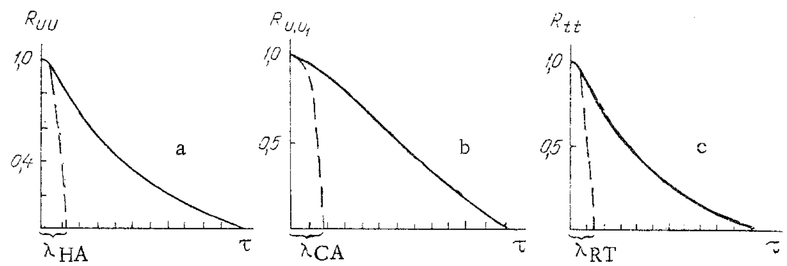

Fig. 3. Autocorrelation functions measured with: a) hot-wire aneomometer; b) conduction anemometer; c) resistance thermometer.

We thus determined the statistical characteristics of the velocity and temperature fluctuation fields by calculating piecewise-continuous realizations on the D3-28 computer in digital form. The sensing elements of the contact resistance thermometer and hot-wire anemometer were physically arranged in close proximity to one another, with the cold filament of the RT in front of the HA wire. The sensing element of the conduction anemometer was placed 40 cm from the elements of the HA and the contact RT. The cross-correlation coefficient of the HA and RT signals were equal to 0.56. The cross-correlation coefficients of the CA signal with the HA and RT signals were equal to ±0.06.

Figure 3 shows the calculated autocorrelations. The samples were taken in time intervals of 0.0468 sec. The data were averaged over several thousand samples until convergence was attained. Besides the autocorrelations, parabolas are drawn through the vertex, the point correspndong to the first sample, and a point calculated on the time axis from the first realization. The intersections of the parabolas with the time axis characterize the Taylor time microscales. It is evident from the graphs that the microscales measured with the HA and the RT practically coincide, whereas the microscales determined from the CA signals are about 30% too high, a result of the size of the conduction anemometer sensing element. In addition to the moments of the signals, the moments of their derivatives were also calculated in the measurements, making it possible to calculate the Taylor time and space microscales [2]:

$$\lambda_\tau = \left[\overline{U}^2 \Big/ \left(\frac{\partial \overline{U}}{\partial \tau}\right)\right]^{1/2}; \quad \lambda_U = U\lambda\tau.$$

Following are the results of the calculations:

Hot-wire anemometer velocity signal $\lambda_{\tau HA} = 5.24 \cdot 10^{-2}$ sec ($5.62 \cdot 10^{-2}$ sec according to the graph); $\lambda_{UHA} = 4.12 \cdot 10^{-1}$ cm;

conduction anemometer velocity signal $\lambda_{\tau CA} = 7.96 \cdot 10^{-2}$ sec ($8.4 \cdot 10^{-2}$ sec according to the graph); $\lambda_{UCA} = 6.37 \cdot 10^{-1}$ cm;

temperature signal $\lambda_{\tau RT} = 5.33 \cdot 10^{-2}$ sec ($5.6 \cdot 10^{-2}$ sec according to the graph); $\lambda_{URT} = 4.27 \cdot 10^{-1}$ cm.

Whereas the microscales differ in the graphs, the (outer) macroscales characterized by the intersection of the autocorrelation functions with the time axis practically coincide. As an example we calculate the integral dynamic scale from the HA signals according to the familiar expression [3]

$$\Lambda_U = U \int_0^1 R_U(\tau)\, d\tau.$$

After the calculations we obtain $\Lambda_U = 71.3$ cm. We carry out a simple calculation on the assumption that a measurement point in the test region near the bottom can be regarded as existing in a fully developed boundary layer. The thickness of the boundary layer can be set equal to 0.1 times the depth H. The measurement depth at the station location was equal to 21 m. The ratio $\Lambda u/\delta$, where δ is the thickness of the boundary layer, is found to be equal to 0.34. All published measurements in boundary layers give this quantity between the limits 0.3-0.4 [4]. Our measurement apparatus and procedure can therefore be deemed reliable.

It is important to note, in addition, the high intensity of the velocity fluctuations, which attained 14% in our measurements, and the comparatively low intensity of the temperature fluctuations, which did not exceed 1.3%.

It can be inferred from the measurements of the higher-order moments of the signals and their derivatives that the investigated process deviates from a Gaussian process. For example, the kurtosis is equal to 7.52 (in contrast with the value of 3 for a Gaussian process), while the skewness parameter is equal to 0.685 (for a normal distribution the odd moments are equal to zero). The skewness parameter of the derivatives of the velocity fluctuations are found to be equal to 0.13-0.54, which is typical of a boundary layer [4]. The intermittency factor is equal to unity everywhere.

To estimate the upper bound of the dissipative frequency spectrum we calculate the Kolmogorov frequency on the assumption of isotropy. Then the dissipation function can be written in the form [2]

$$\epsilon = 15\nu \left(\frac{\overline{\partial U}}{\partial \tau}\right)^2 / U^2$$

and the Kolmogorov frequency is

$$N_K = \epsilon^{1/4} \nu^{-3/4} U/2\pi.$$

The calculations give $\epsilon = 18.7\ cm^2/sec^3$ and $N_K = 56.4$ Hz.

The following conclusions can be drawn from our measurements under natural conditions: The automated measurement system is reliable in service; the software developed for it can be used to compute a large set of statistical parameters characterizing the fine structure of oceanological processes; the programs operate reasonably economically and efficiently; measurements of the one- and two-point moments indicate that the bottom zone in the experimental test region can be treated as a fully developed boundary layer, on which are superimposed modulated polycyclic processes, which can be filtered out in two-dimensional spectral processing.

NOTATION

H, probe submersion depth; λ_T, Taylor time microscale; λ_U, Taylor space microscale; Λ_U, velocity macroscale; δ, boundary layer thickness; ϵ, dissipation function; N_K, Kolmogorov function; R_{UU}, $R_{U_1U_1}$, R_{tt}, autocorrelation functions; Indices: CA, HA, RT, measurements performed with a conduction anemometer, hot-wire anemometer, and resistance thermometer, respectively.

LITERATURE CITED

1. I. L. Povkh, Aerodynamic Experiments in Mechanical Engineering [in Russian], Mashinostroenie, Leningrad (1974).
2. J. O. Hinze, Turbulence, McGraw-Hill, New York (1959).
3. D. I. Grinval'd, "Some results of natural investigations of riverbed flows," in: Turbulent Flows [in Russian], Nauka, Moscow (1976).
4. L. S. G. Kovasznay, "Structure of the turbulent boundary layer," Phys. Fluids, 10, No. 9/11, 525-530 (1967).

DIFFUSION AND MIXING OF PASSIVE IMPURITIES IN A LINEAR VELOCITY FIELD

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It is shown that the mixing process is described by a Lagrangian Green's function. The latter is obtained at both the dynamical and the statistical levels, which permits application of the results to turbulent media.

The question of the mixing of substances down to the molecular level occupies a special position in the problem of chemical reactions in turbulent media [1]. The mixing of substances is conditioned by molecular diffusion, which can play an appreciable role only at distances on the order of the internal scale of turbulence, where a linear dependence of relative velocities on distance holds.

The dynamical problem of diffusion of a scalar passive impurity in an unbounded linear velocity field was investigated in [2-5]. A study of the statistical characteristics of the field of a passive impurity in a medium with linear velocities was the subject of [6-8], where the structure function and short-wavelength asymptotic form of the concentration spectrum were obtained. A number of precise analytical results, particularly the spectrum of

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