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MEASUREMENT OF THE FLUID FLOW VELOCITY BY AN ACOUSTIC FREQUENCY—PHASE METHOD

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New frequency—phase acoustic methods are described as well as the principles for apparatus realization of the recording the flow parameters of a fluid (sea) medium possessing elevated sensitivity and low inertia.

The most extensively used devices at the present time for the determination of the mass-transfer characteristics, for instance, the flow velocities of fluid (marine) media, are vane-type devices based on a mechanical method of measurement. The possibilities of these traditional apparatus with respect to sensitivity, accuracy, and time resolution are restricted and practically exhausted. Thus, for example, the accuracy of measuring the flow velocity of one of the last serially manufactured devices of the type ATsIT [1] with a vane-type flow velocity sensor does not exceed 3-4 cm/sec.

To obtain the background characteristics of a marine medium, to investigate its fine structure, and to study the energy exchange between the ocean and the atmosphere, the circulation of vortex flows, the wake of typhoons, etc., the accuracy and sensitivity of the flow velocity measurements must be raised substantially and the sensor inertia must be diminished.

Most promising in these respects are acoustic methods. When they are used, the flow velocity is determined by the difference in the times of ultrasonic signal (pulse) passage with and against the flow in the liquid (gaseous) medium being investigated, or the phase shift of the received and emitted ultrasonic oscillations caused by the motion of the medium, or by the magnitude of the Doppler effect that occurs during reflection of the ultrasonic wave from the inhomogeneities of the moving medium [1, 2]. However, these methods do not afford the possibility of simultaneous measurement of the magnitude of the flow velocity and acceleration.

The Institute of Heat and Mass Transfer (ITMO) of the Academy of Sciences of the Belorussian SSR in conjunction with the Institute of Applied Physics (IPF) of the Academy of Sciences of the Belorussian SSR and the Far-East Scientific-Research Institute (DVNII) of

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the Goskomgidromet have developed a local flow velocity vector meter for the local determination of the current velocity (acceleration) vector and their fine-scale fluctuations. Its operating principle is based on utilization of the nonstationary Doppler effect and the phase shift of acoustic waves between a receiver and emitter [3-6]. A rise in the accuracy of measuring the flow velocity and acceleration is achieved because of the improvement in the interference-immunity of the system and the application of phase amplification of the two signals used. The sensor of the apparatus consists of three acoustic channels with mutually perpendicular arrangement, each of which measures the magnitude or the variation of the velocity vector projection on the acoustic base line. The singularity of each channel is that it contains two pairs of emitting—receiving piezotransducers (Fig. 1) located so that continuous ultrasonic oscillations are transmitted in the forward and reverse directions through the very same section of the medium being checked. This assures high interference-immunity of the channel. Indeed, a change in the temperature, salinity, pressure, and other properties affecting the sound speed in a medium will cause frequency—phase shifts of identical sign for ultrasonic oscillations being propagated in the mutually perpendicular directions, and they will cancel by subtraction. The frequency--phase shifts due to a change in the flow velocity for the mentioned ultrasonic waves will have different signs and their magnitudes will combine during subtraction.

A convective Doppler effect [7] occurs for one measuring channel, shown in Fig. 1, as the flow velocity (and direction) changes. The magnitude of the phase shift here for a beam l_1 is

$$\Delta f_1 = \frac{f_0 l_1}{(v + u_x)^2} \frac{du_x}{d\tau}; \tag{1}$$

while the reverse beam with base l_2 has an analogous magnitude

$$\Delta f_2 = -\frac{f_0 l_2}{(v - u_x)^2} \frac{du_x}{d\tau}, \tag{2}$$

where f_0 is the frequency of the oscillations being emitted, and u_x is the velocity vector projections on the acoustic base line, taken as the x axis (the direction from the emitter 5 to the receiver 6 is taken as the positive direction). In deriving (1) and (2) we neglected the transverse effect of the frequency shift [7] since it is approximately v/u times less than the longitudinal (for real marine medium currents the ratio u/v is on the order of 10^{-3} or less). This latter circumstance indicates that the acoustic emitter—receiver system in seawater will react just by a change in the velocity vector component along the base independently of whether it is caused by a change in the magnitude of the current velocity or direction. If the acoustic bases l_1 and l_2 are selected identical ($l_1 = l_2 = l$), then the expression for the resultant difference in the oscillations frequencies received by the receivers 6 will have the form (taking into account that $u \ll v$)

$$\Delta f = \Delta f_1 - \Delta f_2 = 2A \frac{du_x}{d\tau}, \tag{3}$$

where $A = f_0 l/v^2$ = const is the acoustic constant of the device.

We find from (3) that

$$\frac{du_x}{d\tau} = \frac{1}{2A} \Delta f. \tag{4}$$

Taking account of the assumptions made, we obtain the corresponding expression for the phase shift by integrating (3):

$$\Delta\varphi(\tau) = 2\pi \int_0^\tau \Delta f(\tau)\, d\tau = 4\pi A \Delta u_x(\tau), \tag{5}$$

from which

$$\Delta u_x(\tau) = \frac{1}{4\pi A} \Delta\varphi(\tau). \tag{6}$$

Therefore, recording the frequency shifts of the acoustic waves yields information about the instantaneous acceleration of the flow, and recording the phase shifts yields information about the current velocity.

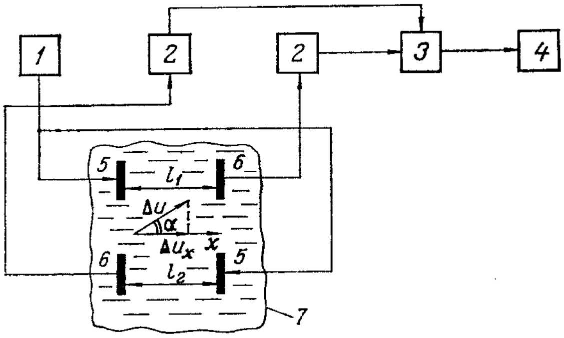

Fig. 1. Block diagram of the fluctuation meter for one flow velocity vector component: 1) quartz sinusoidal oscillation generator; 2) amplifiers; 3) frequency—phase shift meter; 4) information processing and recording system; 5) ultrasonic wave emitters; 6) wave receivers; 7) marine medium.

If a rectangular x, y, z reference system is introduced for which the axes are oriented, respectively, relative to the magnetic meridian, then expressions analogous to (4) and (6) can be written for each current velocity and acceleration vector component. Setting the acoustic bases of the three measuring channels along the axes indicated, we can simultaneously measure the following six quantities:

$$\Delta u_x(\tau)=\frac{1}{4\pi A}\Delta\varphi_x(\tau);\quad \Delta u_y(\tau)=\frac{1}{4\pi A}\Delta\varphi_y(\tau);\quad \Delta u_z(\tau)=\frac{1}{4\pi A}\Delta\varphi_z(\tau); \tag{7}$$

$$\frac{du_x}{d\tau}=\frac{1}{2A}\Delta f_x;\quad \frac{du_y}{d\tau}=\frac{1}{2A}\Delta f_y;\quad \frac{du_z}{d\tau}=\frac{1}{2A}\Delta f_z. \tag{8}$$

This permits determination of the variation in the velocity magnitude

$$\Delta u(\tau)=\sqrt{\Delta u_x^2(\tau)+\Delta u_y^2(\tau)+\Delta u_z^2(\tau)}=\frac{1}{4\pi A}\sqrt{\Delta\varphi_x^2(\tau)+\Delta\varphi_y^2(\tau)+\Delta\varphi_z^2(\tau)} \tag{9}$$

and the instantaneous flow acceleration

$$\frac{du}{d\tau}=\sqrt{\left(\frac{du_x}{d\tau}\right)^2+\left(\frac{du_y}{d\tau}\right)^2+\left(\frac{du_z}{d\tau}\right)^2}=\frac{1}{2A}\sqrt{\Delta f_x^2+\Delta f_y^2+\Delta f_z^2}\,. \tag{10}$$

The direction cosines of the velocity vector

$$\cos\alpha_x=\frac{\Delta u_x}{\Delta u};\quad \cos\alpha_y=\frac{\Delta u_y}{\Delta u};\quad \cos\alpha_z=\frac{\Delta u_z}{\Delta u}. \tag{11}$$

are also found from (7) and (9). The direction cosines of the acceleration vector are determined from relationships (8) and (10) analogously to (11).

The block diagram of a channel to measure the variations in one of the current velocity vector components (they are all identical) is represented in Fig. 1. From the quartz master oscillator 1 a continuous signal is delivered through a sealed coaxial cable to the emitting piezotransducers 5, the signals from the receiving piezotransducers 6 proceed in the same way to the identical resonance amplifiers 2 from whose output they are delivered to the two inputs of the frequency—phase shift meters 3 and from thence the information goes to the processing and recording module 4.

A modification of the single-channel current velocity variation meter was used in 1978 and 1979 expeditions, based on a marine hydrophysical sounding complex developed in ITMO jointly with the IPF [3]. A 5-MHz frequency signal with amplitude on the order of 1.5 V was delivered from the quartz oscillator to half-wave piezoceramic emitters. The frequency—phase shift meter was made on the basis of a serially manufactured frequency comparator Ch7-5 that multiplies the input signal difference frequency and the change in their phase difference, respectively, by M = 2, 20, 200 times (for 5 MHz) to assure a just as great

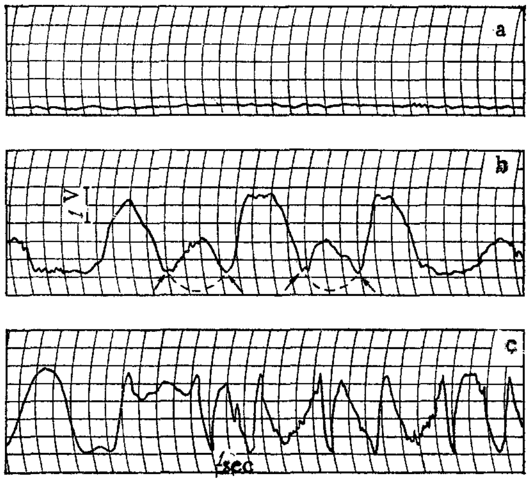

Fig. 2. Examples of current velocity fluctuation oscillogram records at a 100-m depth (120-m depth) for a recording voltmeter rate of 5 mm/sec and a 1 V/cm sensitivity: a) transverse fluctuations in the horizontal plane (perpendicular to the flow velocity) u_y; b) longitudinal fluctuations in the horizontal plane (in the current direction) u_x; c) vertical u_z.

magnification of the sensitivity and accuracy in measuring the flow velocity and acceleration variation. The value of the coefficient M is set before the beginning of the experiment. The phase shifts occurring in the acoustic channel and amplified in the comparator are measured by using the balanced phase detector of the frequency comparator. A signal from the phase detector output, with a normalized maximal value of the voltage $V_{max} = \pm 2.2$ V (which corresponds to the range of variation multiplied by M times the phase shift $\Delta\varphi_{max} = \pm\pi/2$) is later delivered through a multichannel electronic commutator to the analog—digital transducer of the probe described in [3]. The value of the smallest discrete place in the analog—digital transducer is $V_{max} \cdot 2^{-7}$ V. It is hence clear that in a linear approximation (without taking account of the nonlinearity of the detector amplitude—phase characteristic) this affords a possibility for measuring the phase shifts multiplied M times with the error (expressed in degrees of angle)

$$\delta\varphi = \frac{\Delta\varphi_{max}}{2^7} \approx 1°. \tag{12}$$

Taking into account the multiplication factor M = 2, 20, 200, the real phase shifts occurring because of the current velocity variations are here measured with the respective errors

$$\delta\varphi = 0{,}5°; \qquad \delta\varphi = 0{,}05°; \qquad \delta\varphi = 0{,}005°. \tag{13}$$

Utilizing these values, we can estimate the least possible measurement error as well as the range of velocity variation since the phase detector measures the phase shifts uniquely only in the range $\pm\pi/2$. To do this we turn to (6). The length of the acoustic base was 0.152 m in the apparatus realized. Then taking the value V = 1500 m/sec for the velocity of ultrasound at $f = 5 \cdot 10^6$ Hz for seawater, we obtain for the error in measuring the current velocity fluctuations in conformity with (12) and (13): $\delta u = 2.3 \cdot 10^{-3}$ m/sec (without multiplication), $\delta u = 1.15 \cdot 10^{-3}$ m/sec, M = 2; $\delta u = 1.15 \cdot 10^{-4}$ m/sec, M = 20; $\delta u = 1.15 \cdot 10^{-5}$ m/sec, M = 200.

The formula

$$\Delta u_{max} = \frac{1}{4\pi} \frac{v^2}{f_0 l M} 2\Delta\varphi_{max} = \frac{1}{4} \frac{v^2}{f_0 l M} \tag{14}$$

is valid for determination of the range of current velocity variations accessible to measurement. Substituting the data, we obtain $\Delta u_{max} = 0.46$ m/sec (without multiplication), $\Delta u_{max} = 0.23$ m/sec, M = 2; $\Delta u_{max} = 0.023$ m/sec, M = 20; $\Delta u_{max} = 2.3 \cdot 10^{-3}$ m/sec, M = 200.

It is seen from the estimates presented that the relative error in current velocity fluctuation measurement is identical, equal to 0.5%, in all the ranges; however, the interval of the velocity variations being measured radically becomes narrower as M increases. In reality, the relative error grows somewhat as M increases because of apparatus noise which is magnified as the phase multiplication factor increases.

The electronic part of the measuring system to be submerged was placed structurally in a metal cylindrical housing, the acoustic sensor was sufficiently remote from it, and stabilizing keels were placed on opposite sides. Consequently, the current sensor was in the unperturbed free stream, while the probe housing and the stabilizers were downstream. The acoustic base was oriented so that the current velocity fluctuations could be recorded along and across the flow in the horizontal and vertical planes.

The method of operation was the following. First, the received signal difference frequency without multiplication was measured. The probe to be submerged was lowered to a definite depth on a hawser cable from the scientific-research vessel, and the current velocity fluctuations were recorded on a millivoltmeter recorder to which the signal was delivered from the appropriate channel of the digital—analog transducer of the on-board part of the measuring complex. Then the magnitude of the multiplication factor M was set in to assure uniqueness of the measurements for higher sensitivity of the device. Examples are presented in Fig. 2 of the current velocity fluctuation oscillogram records at a 100-m depth in the area of the Kurile Islands (for a total depth of 120 m).

Since the measurements were performed in mode of sounding from on board ship while drifting, the ship roll and drift exerted influence on the measurement results, in addition to the natural current pulsations of the medium. The vertical pulsations here turned out to be outside the limits of the sensor measurement range, they are due mainly to ship roll: the maxima and minima on the loop oscillogram clearly correlate with the period of the roll which was 3-7 sec. The current velocity fluctuations along the stream were also sometimes outside the measurement range limits, as is seen by the characteristic breaks in the oscillogram. These breaks are marked with arrows in Fig. 2, where the extrapolated dependence of the phase shift that corresponds approximately to the actual curve is shown dotted. The mean range of longitudinal fluctuations is ±0.3 m/sec with the extrapolation used taken into account. Ship drift and its associated hawser-cable vibrations exerted influence on the results of measuring the longitudinal fluctuations. The transverse velocity fluctuations measured in the horizontal plane are closest to the natural value since neither the vertical displacements of the probe because of ship roll nor the ship drift introduced interference because of the smallness of the transverse effect in this case. The mean range of the indicated fluctuations was $\pm 4 \cdot 10^{-2}$ m/sec. On the whole, the results obtained confirmed the high sensitivity of the frequency—phase acoustic method of measuring the current velocity variations under in situ conditions.

On the basis of the investigations performed, a local velocity vector meter has been developed on the basis of the instrument ATsIT [1] at this time, in which the current velocity recording channels of mechanical (vane) type are replaced by acoustic type. The current velocity vector components are determined independently in the horizontal plane, and the vertical velocity vector component is measured separately.

The device is based on using a phase acoustic method. Taking account of the current velocity the expressions for the phase difference in the oscillations received separately by the receivers 6 relative to the emitters 5 of each sensor acoustic channel (see Fig. 1) have the form

$$\Delta\varphi_1 = -2\pi f_0 \tau_1 = -2\pi f_0 \frac{l_1}{v + u_x}; \quad (15)$$

$$\Delta\varphi_2 = -2\pi f_0 \tau_2 = -2\pi f_0 \frac{l_2}{v - u_x}; \quad (16)$$

where τ_1 and τ_2 are the times of wave passage between the receiver and emitter of the first and second channels.

The acoustic oscillation phase difference between the receivers 6 equals

$$\Delta\varphi = \Delta\varphi_2 - \Delta\varphi_1 = -2\pi f_0 \left(\frac{l_2}{v - u_x} - \frac{l_1}{v + u_x} \right) = -4\pi A u_x - 2\pi f_0 \frac{\Delta l}{v}, \quad (17)$$

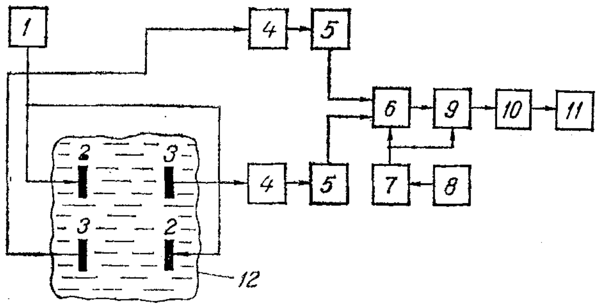

Fig. 3. Block diagram of the meter for one component of the absolute value of a current velocity vector: 1, 8) quartz sinusoidal oscillation generators; 2, 3) ultrasonic wave emitters and receivers, respectively; 4) amplifiers; 5, 7) pulse shapers; 6) comparison unit; 9) converter unit; 10) storage module; 11) ATsIT device; 12) sea medium.

where $\Delta l = l_2 - l_1$ is the dissimilarity in the base distances of the two acoustic channels for one sensor, and the remaining assumptions for the solution (17) are taken just as in the derivation of (3) and (5).

The second term in (17)

$$\Delta\varphi_3 = -2\pi f_0 \frac{\Delta l}{v} \tag{18}$$

is the phase difference between the oscillations received in the unperturbed (fixed) medium for dissimilar bases, i.e., for $u_x = 0$; in case $l_1 = l_2 = l$ it equals zero. Since it is difficult to achieve strict compliance with the condition $l_1 = l_2$ in practice, the quantity $\Delta\varphi_3$ can be determined experimentally for measurements in a fixed medium. This phase difference can be compensated in a measuring apparatus by a phase shifter connected in series in the loop of one of the channels. If these conditions are satisfied, then the magnitude of the current velocity component will equal

$$u_x = -\frac{1}{4\pi A} \Delta\varphi. \tag{19}$$

Therefore, the phase shift of the acoustic oscillations in this two-channel measuring system is determined just by the flow velocity.

We obtain three current velocity vector projections u_x, u_y, u_z, the magnitude of its absolute value, and the direction cosines for the x, y, z coordinate system used with the correspondingly oriented sensor bases, analogously to (7), (9), and (11).

The phase shift of the acoustic oscillations between two receivers for each sensor in the apparatus developed is converted into a time interval $\Delta\tau$ relative to the lower clock frequency f_c that assures uniqueness of the phase measurement within the limits of the period 2π, the necessary range of measurement and sensitivity in the current velocity. The phase difference for the clock frequency is determined by the known relationship

$$\Delta\varphi = -2\pi f_т \Delta\tau. \tag{20}$$

Substituting this quantity into (19) we obtain a computational formula to find the current velocity by this method

$$u_x = \frac{f_т}{2A} \Delta\tau_x = \frac{v^2}{2l} \frac{f_т}{f_0} \Delta\tau_x. \tag{21}$$

The maximal value of the current velocity will hold when the magnitude of the time interval reaches the greatest uniquely determined value, i.e., becomes equal to the clock frequency period $T_c = 1/f_c$. In this case, as follows from (21)

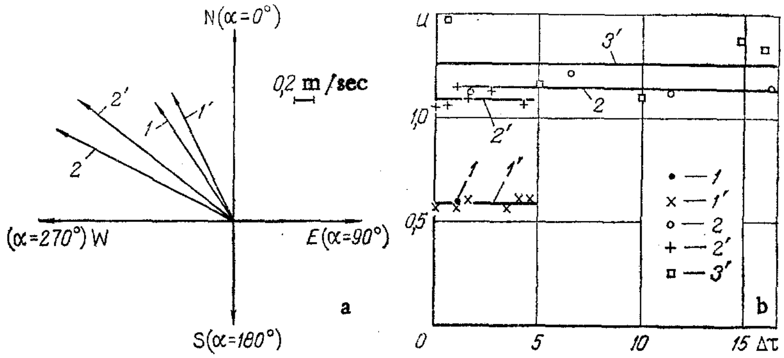

Fig. 4. Indian Ocean equatorial current velocities recorded by the devices BPV-2 and TIT: a) hodographs of the average vectors on 10 m 1) BPV-2: u = 0.59 m/sec, α = 327°; 1') TIT: u = 0.585 m/sec, α = 339°) and 300 m 2) BPV-2: u = 1.34 m/sec, α = 294°; 2') TIT: u = 1.276 m/sec, α = 308° horizons; b) instantaneous and average values at the 10 m 1) for BPV-2, 1') for TIT; 216 m 2) for BPV-2, 2') for TIT; 300 m 3') for TIT horizons.

$$u_{max} = \frac{1}{2A} = \frac{v^2}{2lf_0}. \tag{22}$$

For the simultaneous measurement of the absolute value and the fluctuations of the flow velocity, the magnitude of the initial time interval in a fixed medium can be set equal to half the clock frequency period. In this case the value u_{max} will be half that in (22)

$$u'_{max} = \pm\frac{1}{4A} = \pm\frac{v^2}{4lf_0}. \tag{23}$$

A block diagram is shown in Fig. 3 for a meter for one current velocity component in which the phase shift converted into a time interval is measured by using a discrete logic circuit. The purpose of modules 1-4 is the same as in the apparatus displayed in Fig. 1. The harmonic signals from the amplifiers 4 go to the pulse shaper modules 5 and then to the comparison unit 6, where the time shift between the signals to be compared from the receivers 3 in shaped. Here a signal from the other quartz generator 8 with frequency close to the frequency of the generator 1 goes through the pulse shaper 7. Afterwards, a time shift in the form of rectangular pulses with repetition rate equal to the difference frequency of generators 1 and 8 is shaped at the output of the circuit 6. As already noted, the clock frequency is selected by starting from a given sensitivity and range of velocity of the current velocity. Then counting of the time signal duration occurs in the module 9 by filling it with pulses from the quartz generator 8 after which the signals enter the storage module 10 and go from there to the appropriate stages 11 of the ATsIT device.

The measuring system can operate in the autonomous mode while recording information on magnetic tape for subsequent read-out by using the on-board data-processing apparatus; information in a binary code can be transmitted through the hawser cable to the apparatus on board the ship.

The computed sensitivity of the initial version of the device was $1.5 \cdot 10^{-3}$ m/sec for the current velocity in the range to ±2 m/sec, but it can be raised by diminishing the range of measurement or increasing the accuracy of measurement of the time interval.

Tests which the described version of the device underwent in in situ conditions during a 1981 expedition in the Okhotsk Sea on the scientific-research vessel *V. Uryvaev* confirmed its high sensitivity and low inertia.

A modernized version of this hydrophysical measuring complex TIT was used in October 1983-January 1984 in the 23rd voyage of the scientific-research vessel *Akademik Shirshov* to study the scale and time variability of water mass circulation from the near-surface layer to a depth of 500 m in the Indian Ocean in the equatorial current zone from 90 to 65°

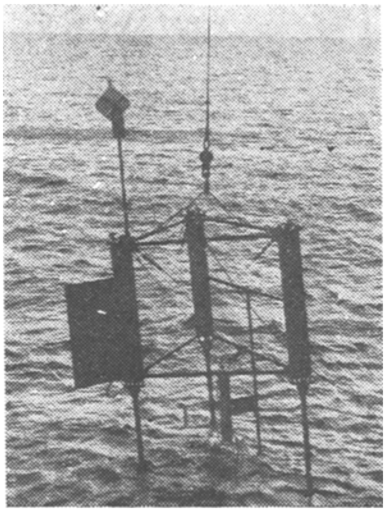

Fig. 5. External view of the stabilized platform PSM with acoustic TIT meter mounted on it at the time of its being lowered from on board the research vessel *Akademik Shirshov*.

E along the equator and in the area of the intertropical convergence zone along the 65th meridian from 10° N to 20° S. The measurements were executed in the sounding regime by using a hydrological winch from on board the research vessel with direct transmission of the information to be recorded along the hawser-cable to the on-board data-processing apparatus with recording in digital form (octal code) on a teletype machine. The current velocity was also recorded simultaneously with the device TIT by using a BPV-2 vane meter which was located alongside with its submerged part.

A comparative analysis of the results obtained by the TIT and BPV-2 devices permitted estimation of the average and fluctuation values of the current velocity in both magnitude and direction in the above-mentioned regions (i.e., the current velocity vector fluctuations were estimated).

The results obtained on the structure of the surface currents differed somewhat from the surface current map presented for a given time of year in the Atlas of Oceans [8], which apparently needs refinement. Presented as an illustration in Fig. 4 is a hodograph of the current velocity vector from the devices TIT and BPV at depths of 10 and 300 m in the equatorial current zone of the Indian Ocean in the area of intersection of the equator with the 67° E meridian (total depth 2700 m). As is seen from Fig. 4a, the velocity vectors measured by the devices TIT and BPV are in good agreement, the relative deviation of their average values did not exceed 5.5% in absolute value (not more than 1% at a 10-m depth), and not more than 8% in direction (4% at a 10-m depth). The relative deviation was systematic in nature.

The time dependence of the instantaneous and measured values of the current velocities at this same point in the Indian Ocean is shown in Fig. 4b for depths of 10, 216, and 300 m, recorded by the devices BPV-2 and TIT. The current velocity increased as the depth increases, which corresponded to existing data [8]; however, the investigations performed showed that the current structure was of large-scale vortex-like nature. The level of the current velocity fluctuations relative to the average values recorded by the TIT acoustic meter did not exceed 5% at the 10-m and 216-m depths. As the depth increased, the fluctuation level grew to 8% at the 300-m horizon. This is explained by the increase in the velocity gradient of equatorial currents with depth.

The analysis performed permits making the deduction that the acoustic measuring complex TIT, which is practically without inertia as noted above, permits the recording of instantaneous current velocity field fluctuations.

Currents in the near-surface layer of the marine medium were studied to 5 m depths in addition to the described hydrophysical investigations. The investigations were performed in the autonomous mode by using a floating stabilized platform developed and fabricated in ITMO of the Academy of Sciences of the Belorussian SSR. It assured placement of the submerged part of the TIT (or any other device of weight up to 100 kg) in the near-surface sea water layer at 0.5-5 m horizons and was intended to eliminate the influence of slight sea waviness, hawser-cable vibrations, and other perturbing factors on the measurement results. In this mode the TIT device inscribed the recorded information in discrete form on a built-in magnetic carrier with subsequent reproduction and processing of the inscribed data on board the research vessel.

The external view of the floating stabilized platform PSP is shown in Fig. 5 with the acoustic current meter TIT mounted at the time of its being lowered in the southwestern part of the South China Sea by the stern cargo crane.

All the described measurements on the 33rd voyage of the research vessel *Akademik Shirshov* were conducted simultaneously from the standard hydrological station arrangement by using a probe-bathometer. This permitted estimation of the confidence of the information recorded by the TIT device for other physical parameters: temperature, salinity, pressure.

Deep-water tests of the acoustic measuring complex TIT were conducted in the South China Sea at depths to 2400 m, which confirmed its normal operability, high sensitivity, low inertia, and promise for further utilization to study the fine structure of the current velocity fields of a sea medium.

The investigations performed during the voyage permitted also clarification of the individual structural disadvantages of the measuring complex in the interests of its further modernization.

NOTATION

v, velocity of acoustic wave propagation in the medium; u, current velocity of the medium; τ, time; f, oscillation frequency; φ, oscillation phase; α, angle between the direction from the source to the receiver and the current direction; l, base distance of the sensor.

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