STRUCTURE OF STRATIFIED FLOW AROUND A CYLINDER
AT LOW INTERNAL FROUDE NUMBER

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The flow pattern around a horizontal cylinder towed at constant velocity in a continuously stratified fluid is visualized by the shadow method. The velocities in the leading flow disturbance, i.e., in the flow-blocking region ahead of the cylinder, are presented. In the body wake, a new class of small-size structures in the density gradient field is revealed against the background of a smooth velocity profile. The evolution of the flow pattern with variation of the parameters of body motion is studied.

Measurements using highly sensitive devices, which have become regular since the late 1960s, have revealed a large number of periodic finely structured features in both vertical profiles and horizontal sections of physical fields of the ocean and atmosphere. In these fields, relatively thick uniform layers are separated by thin high-gradient interlayers and fronts. Specific internal waves and local small-scale vortices that can be generated in the interlayers constitute wave-vortex turbulence. This turbulence was observed in summer thermoclines [1] and deeper in the ocean. However, data of full-scale observations were insufficient to determine the mechanisms of formation and preservation of discontinuities in the density and its gradients that counterbalance the smoothing effect of diffusion processes and to estimate the influence of perturbations of the density field on the flow stability and transport of active or passive additives.

It turned out that changes in continuous stratification and the stability of structures that arise are conveniently studied using two- and three-dimensional wake flows [2–5]. Contact measurements showed that in the high-gradient interlayers that bound a two-dimensional laminar wake, the initial density gradient increases by a factor of 10–150 [4]. In this wake, along with large-scale vortices, small-scale vortices can be observed, with the sizes dependent on the interlayer thickness. Examples of various types of instability of wave flow that result in the formation of “spear-shaped” structures in a wake and wave-vortex surfs and high-gradient interlayers downstream of dangling vortices in the body wake are reported in [5].

Discontinuities in the density and its gradient are an important part of the wake flow in an initially continuously stratified fluid. They bound the regions of existence of large-scale phenomena such as attached internal waves, vortices, and their systems (dangling or submerged in the wake) and influence transport of active and passive additives and propagation of electromagnetic and acoustic waves.

The purpose of this work was to study one type of fine structures that are related to the previously unstudied flow instability in the immediate vicinity of a body moving with constant velocity in a deep, continuously stratified fluid at rest.

Determining Parameters. The complete system of fluid-dynamic equations describing nonuniform fluid flow around an obstacle includes equations of state, continuity, and conservation of salt and momentum, and boundary conditions (conditions of attachment for the velocity and nonpenetration for the material on the solid surface).

A stratified fluid is a nonequilibrium medium in which diffusion-induced compensating flows originate on the inclined impermeable boundaries blocking the molecular flow of a stratifying component even in the

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absence of external disturbances [6]. These boundary flows exhibit different scales of variation in velocity and density (salinity), whose ratio is independent of time and is determined by the Schmidt number. These features remain after separation of the split boundary layer from the body. Accordingly, both in the immediate vicinity of and far away from the body there are flow regions (high-gradient interlayers) whose dynamics depends greatly on the molecular properties of the medium.

Stratified flow around an obstacle is determined by the following dimensional parameters: the density ρ₀ and its gradient dρ₀/dz, the kinematic viscosity ν and diffusivity κₕ of the salt, the velocity U and dimensions D of the body, and the free-fall acceleration g. From a methodical viewpoint, it makes sense to use uniform quantities, which, in our case, have the dimension of length. This is not a mere formality: each scale can be put into correspondence with a certain flow structural element (or an element of the problem’s geometry).

The basic scales in the present approach are the following: the buoyancy scale \( \Lambda = |d(\ln \rho_0)/dz|^{-1} \) (the z axis is vertical), the body dimension (e.g., the diameter of the cylinder D), the wavelength of an attached internal wave λ = UTₖ = 2πU/N, where \( T_k = 2\pi/N = 2\pi\sqrt{\Lambda/g} \) is the buoyancy period (N is the frequency), and the thicknesses of the velocity (δₓ = ν/U) and density (δₚ = κₕ/U) boundary layers. These scales are used to construct a denumerable set of combined scales \( L_c = \sqrt[4]{L_x L_y L_z} \ldots \). These derived scales are of different natures; some of them characterize the geometry of the process (including the dimensions of the main structural elements, among which is the so-called viscous wave scale \( L_v = \sqrt{\Lambda / \nu} = \sqrt{g/\nu} / N \), related to the modal structure of harmonic internal waves and the dimension of vortices in the wake past the cylinder or the thickness of their boundaries [3]), and others reflect translational properties or the phenomena caused by the dissipative factors: the viscosity (δₓ = ν/U) and diffusion (δₚ = κₕ/U). Of derived scales that depend on several kinetic coefficients, one can distinguish the scale \( L_w = \sqrt{\nu k_s / N^2} \), which characterizes internal waves of zero frequency (dissipative-gravity waves in problems on convection [7]).

According to this approach, the traditional dimensional parameters in the problem of interest are defined as the ratios of basic scales. For example, the Reynolds number \( Re = D/\delta_v = UD/\nu \) is the ratio of the typical body dimension to the characteristic length of the viscous boundary-layer. Similarly, the Peclet number \( Pe = D/\delta_p = UD/\kappa_h \) is the ratio of the typical body dimension to the thickness of the density boundary layer, the internal Froude number \( Fr = \lambda / 2\pi D = U/N D \) is the ratio of the wavelength of an attached internal wave to the typical body dimension, and \( C = \Lambda / D \) is the ratio of the scales. The Schmidt number is ratio of Pe to Re: \( Sc = Pe/Re \).

In a series of tests performed, the values of the main determining parameters were chosen from the condition of stability of the known flow structural elements (leading disturbance, body wake, and attached internal waves). Nevertheless, there are combinations of parameters that give rise to special small-scale flow structural elements whose degree of distinctness changes smoothly during monotonic variation of one of the dimensional parameters (flow velocity or body diameter). Analysis of our previous studies [3-5] shows that these phenomena occur at moderate Reynolds numbers (Re < 100), at which the flow is stable against large-scale vortex disturbances (Fr < 0.1). In this connection, the experimental procedure was chosen from the condition of simultaneous visualization of large- and small-scale structural elements. The Maksutov method with a vertical illumination slit and a flat or thread-like stop aperture is most conveniently used to solve this problem.

Experimental Procedure. The tests were carried out in a 240 x 40 x 60 cm tank with transparent walls. The tank was filled with a linearly stratified aqueous solution of sodium salt by the method of continuous displacement. Prior to each test, the buoyancy period \( T_k \) was measured by an electric conductivity meter with an accuracy within 5%. In the tests performed, the period was 6.8 sec, gradually increasing to 7.7 sec owing to natural liquid diffusion and mixing.

The flow pattern past a horizontal cylinder of diameter D = 2.5, 5.0, and 7.6 cm was studied. The cylinder was towed with constant velocity in the central part of the tank. It was fastened with thin knives to a carriage which was moved along the guides with a velocity \( U = 0.024-1.0 \) cm/sec (increment ΔU = 0.02 cm/sec and accuracy of velocity determination better than 5%). Prior to each test, the cylinder was placed at the edge wall of the basin. The experimental conditions (\( C = 150-560, Fr = 0.004-0.044, \) and \( Re = 16.5-167 \))