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Soaring Interfaces, Vortices and Vortex Systems inside the Internal Waves Wake Past the Horizontally Moving Cylinder in a Continuously Stratified Fluid

Chashechkin, Yu. D.* and Mitkin, V. V.*

* Laboratory of Fluid Mechanics, Institute for Problems in Mechanics of the Russian Academy of Sciences, 119526, prospect Vernadskogo 101/1, Moscow, Russia.

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Abstract : The flow pattern around a horizontal cylinder towed at constant velocity along isopycnic plane in a continuously stratified liquid is visualized by conventional techniques of “Vertical slit-Foucault’s knife”, ”Maksoutov’s slit-thread” and “horizontal slit-regular grating”. Using sensitive high-resolution methods allows detail studying such component of stratified flow structures as soaring interfaces, singular soaring vortices and vortex systems, which arise directly inside the internal waves field past the cylinder. These flow elements having high level of vorticity are separated from the downstream wake by a strip of fluid without any small-scale inhomogeneities. Formation of singular vortex dipoles on leading edges of soaring interfaces is investigated in details in a wide range of flow parameters.

Keywords : Schlieren technique, Stratified fluid, Horizontal cylinder, Internal waves, Soaring interfaces, Vortex structures.

1. Introduction

Investigations patterns of internal waves, upstream disturbances and downstream wakes past 2D bluff bodies, horizontal and sloping strips (Nakamura, 1991; Chashechkin and Mitkin, 2004) are performed over wide rage of flow parameters. Topology structure of a near vortex wake past the cylinder is investigated and conditions of shedding synchronization which causes increased lift and drag forces are defined by a time-resolved PIV system (Kim et al., 2004). Singular vortices in the wave field past the body were identified as result of the internal waves breaking (Boyer and Davies, 2000). The sensitive schlieren instruments reveal singular interfaces in the internal waves field separated from the body and the wake by a strip of fluid without small scale disturbances (Mitkin and Chashechkin, 1999). These interfaces indicate that the initially smooth stratification is converted into a layered stratification without any turbulence and vortex actions.

Complete classification of infinitesimal periodic motion in a fluid indicates that a periodic wave motion in stratified or rotating fluid is complimented by two types of singular components including boundary layers on solid surfaces (Chashechkin and Kistovich, 2004). These components of the flow are characterized of a high level of vorticity. Fine boundary layers and large-scale internal waves form unified system and they appear and disappear synchronously in spite of difference in their scales. Analogues of boundary layers are soaring interfaces in a fluid interior. Strong interaction of waves and internal boundary currents can lead to formation of vortices on soaring interfaces. The goal of the paper is to study experimentally the process of transformation of a singular soaring interface into singular vortex or set of vortices in the wave wake past the horizontal cylinder uniformly moving in a linearly stratified liquid.

2. Flow Parameters

The dimensional parameters of the problem are velocity U and diameter of the cylinder D, gravitational acceleration g, initial density ρ and its gradient $d\rho / dz$, kinematic viscosity coefficient ν and salt diffusion coefficient κ_s. The density profile $\rho(z)$ is characterised by the buoyancy scale length $\Lambda = \left| d \ln \rho / dz \right|^{-1}$, the buoyancy frequency N and period $T_b = 2\pi / N = 2\pi \sqrt{\Lambda / g}$, z- axis is directed upward.

The external length scales of the problem are buoyancy scale Λ and diameter of the towing body D. Internal structure of the flow is characterised by several intrinsic length scales, i.e., by length of attached (lee) internal waves $\lambda = UT_b$, thickness of the velocity boundary layer $\delta_u = \nu / U$, thickness of the density boundary layer $\delta_\rho = \kappa_s / U$ on the body surface. Detailed analytical and numerical studies reveal transient internal waves and boundary layer in a flow induced by diffusion, which arise due to breaking of diffusion salt flux on a solid surface (Baydulov et al., 2005). This transient layer is characterised by length scales of velocity $\delta_b = \sqrt{\nu / N}$ and density $\delta_\rho = \sqrt{\kappa_s / N}$. The length scales do not depend on the surface slope. There are set of length scales and the unique natural time scale, i.e., the buoyancy period T_b.

The conventional dimensionless parameters can be expressed in terms of direct (Fr, C) or inverse (Re, Pe) ratios of the appropriate scales to the body diameter: internal Froude number $\mathrm{Fr} = U / ND = \lambda / 2\pi D$, length scales ratio $\mathrm{C} = \Delta\rho / \rho = \Lambda / D$, Reynolds number $\mathrm{Re} = UD / \nu = D / \delta_u$ Peclét number $\mathrm{Pe} = UD / \kappa_s = D / \delta_\rho$.

When the obstacle starts, the diffusion induced boundary currents separate from the surface and produce nearly horizontal high gradient interfaces inside the density wake (Baydulov et. al., 1999) preserving their typical transverse length scales. The singular interfaces free of the contact with the boundary layer and having dynamical features on their leading and trailing edges are also observed inside the attached (lee) internal wave field. All these thin interfaces are oriented in the direction of motion.

Essentially less is known about mechanisms of a fine structure formation and transformation of its elements into vortices in a stratified wake past an obstacle. The aim of this paper is to present patterns of the flow around starting horizontal cylinder and to demonstrate the dynamic features of soaring interfaces and mechanism of gradual transformation of their sharp leading edges into vortex systems.

To visualise simultaneously large and thin elements of the flow an optical instrument should have large aperture, high sensitivity and a fine spatial resolution. The sensitive schlieren instrument is used in presented experiments.

3. Experimental Techniques

The scheme of the experimental set-up is presented in Fig. 1. Testing tank (6) with optic windows (7) with dimensions 2.2 x 0.4 x 0.6 m^3 is filled from below with a stratified common salt solution using the well-known two-tanks method. One tank (11) initially is filled by the brine in the density range from 1.005 to 1.2 g/cm^3 and the second one (12) is filled by fresh water. A hollow cylinder (10) is connected by transparent knives (9) to carriage (8) running on rails above the tank.

The side view of the flow pattern is registered by the schlieren instrument IAB-458 (1-5). Due to variations of the density in the tank and dispersion of light the beam is deflected from the straight line. For compensation of this deflection the illuminating and receiving parts of the instrument were placed on independently regulating foundations with 4 degree of freedom (displacements and rotations in the vertical and horizontal planes). In practice a linear distribution of undisturbed density was used when all the light rays are deflected on the same angle so that the beam incident upon the second main mirror is composed of parallel rays. The white light from the source (1) propagates through the illuminating slit. In the receiving part of the instrument (3) different cutting diaphragms that are Foucault's knife, Maksoutov's thread and grating are placed. Lens (4) produces sharp image of the flow on the film (5). Due to natural dispersion of light in the stratified salt water all images are coloured. The colour provides additional important information about general and local structures of the flow pattern. The value and profile of local buoyancy frequency are checked by the density marker method. These markers are produced by a laminar wake past the vertically ascending small gas bubble or a free descending common salt or sugar crystal. Internal oscillations around the vertically submerging marker are observed optically or measured by the conductivity probe. In these experiments the buoyancy period value is changed from 7.4 to 17.5 s.

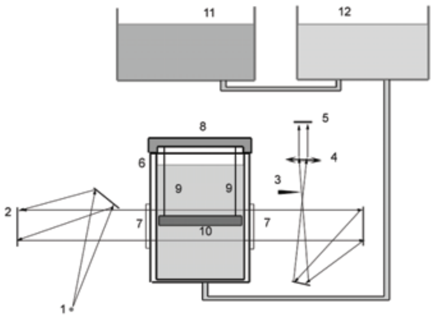
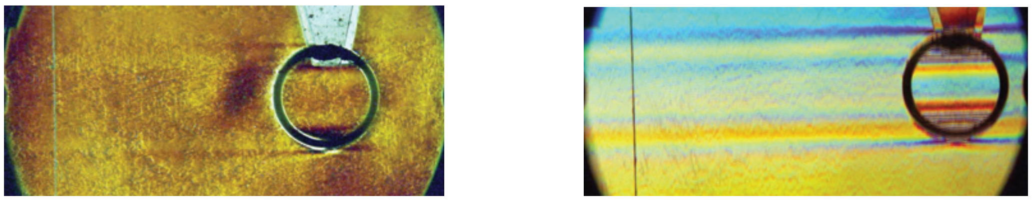


Fig. 1. Experimental set-up.

The plastic cylinder tube (10) with length equal to the tank width (40 cm) and the external diameter of 2.5, 5.0 or 7.6 cm is towed horizontally by means of two vertical transparent blades (9) rigidly fastened to a carriage (8). The carriage moves along rails mounted above the tank (6). The towing speed is selected in the range of 0.03 – 6 cm/s, including regimes of wake bubbles and soaring interfaces (Boyer and Davies, 2000). Each experiment was started after decay of all disturbances induced by previous towing of the cylinder. After finishing of daily program the cylinder was placed in the view field to observe diffusion induced boundary currents on next day.

4. Experimental Results

Common and 'natural rainbow' colour schlieren images of disturbances produced by diffusion induced boundary current on the motionless cylinder tube in a stratified fluid at rest are presented in Fig. 2. Traditional method of visualization (vertical slit-knife in focus) reveals two extended horizontal bands touching upper and lower poles of the cylinder (Fig. 2(a)). Black domains in upper and lower parts inside the cylinder indicate location of regions where initial density gradient is decreased due to interrupting of molecular salinity flux by impermeable solid surface. In the central part of the cylinder tube the density gradient remains unchanged. More sensitive 'natural rainbow' colour schlieren method (Fig. 2(b)) visualizes extended pattern of disturbances produced by diffusion induced flow consisting of four vortices placed in each quadrant. Detailed calculations of 3D diffusion induced flows on a sphere illustrating fine structure of flow in tiny details are produced by Baydulov et al. 2005.

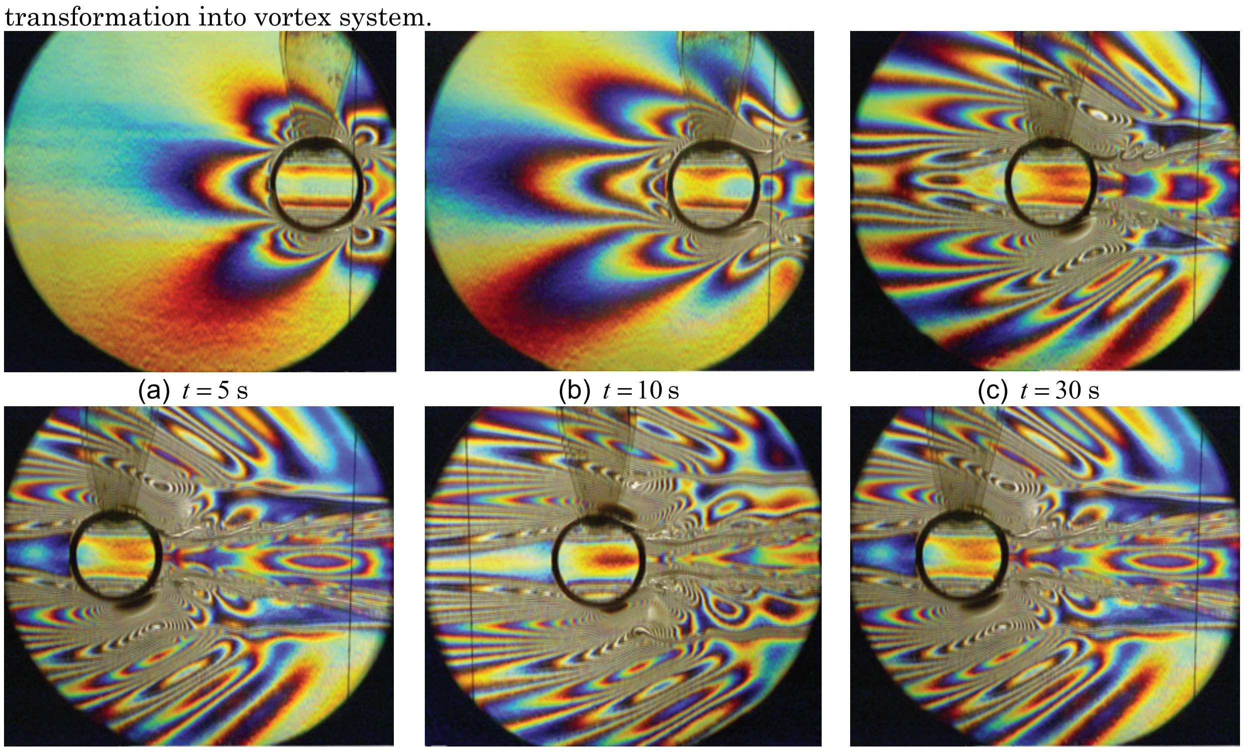


(a) (b)

Fig. 2. Common and colour 'natural rainbow' schlieren images of disturbances produced by diffusion induced boundary current on the motionless cylinder in a stratified fluid at rest ($D = 5$ cm, $T_b = 10.5$ s). Time delay after filling the tank with placed cylinder is 48 hours.

No-slip and no-flux of boundary conditions lead to variation of density and index of refraction profiles inside and outside the cylinder. Attenuation of the gradient inside the cylinder manifests by sequence of horizontal strips in upper and lower parts of the image. Elongated and slightly curved lines touching the upper and lower poles of the cylinder visualise external flow ascending or descending along the cylinder surface and discharging after contacts on the line of flow conjugation on the poles. Colour strips inside the cylinder tube indicate a weakening of initial density gradient caused by no-flux conditions on impermeable solid surface. In the central part density gradient remains unchanged. Observed flow pattern manifests the most intensive part of calculated diffusion-induced flow (Baydulov et al., 2005).

The patterns of density gradient disturbances produced by the diffusion induced boundary currents near the motionless horizontal cylinder in a fluid at rest are presented in Fig. 2. Conventional schlieren image in Fig. 2(a) shows set of high gradient interfaces originating on upper and lower poles of the cylinder. The length of interfaces slowly increases with time; the amplitude of disturbances gradually decays with distance. The flow patterns around cylinder and a horizontal or sloping strip in a fluid at rest are similar (Chashechkin and Mitkin, 2004). When the body starts to move, these diffusion-induced currents separate from the surface and produce high gradient interfaces contacting with the obstacle. Besides interfaces transient and attached (lee) internal waves, as well as blocked fluid ahead and downstream wake past the obstacle, are formed. All these flow components originate from transient modes. Their detailed evolution was described earlier. Patterns of the flows presented here illustrate formation of singular soaring interfaces and their transformation into vortex system.


(a) $t = 5$ s (b) $t = 10$ s (c) $t = 30$ s

(d) $t = 50$ s (e) $t = 75$ s (f) $t = 135$ s

Fig. 3. 'Natural rainbow' schlieren images of flow pattern past the horizontally moving cylinder in the stratified fluid ($D = 5$ cm, $T_b = 10.5$ s, $U = 0.24$ cm/s) at different times after beginning of the motion; a-f) $-\tau = t / T_b =$ 0.48; 0,95; 2.86; 4.76; 7,14; 12.86.

Starting body itself generates large-scale disturbances, and separating diffusion induced boundary flows form high gradient features of downstream flow pattern. Sequence of flow patterns visualized by 'natural rainbow' schlieren method is shown in Fig. 3. Instant start of the body produces a rosette of transient internal waves. Central vertical axis symmetry of the images presented in Fig. 2 is lost immediately after start, and images of waves in the direction of the cylinder motion are more contrast than those in the opposite direction (Fig. 3(a)). Contours of curved strips inside internal waves field in Fig. 3 visualize loci of equal the particles displacements amplitudes. The width of curved strips characterizes local amplitude gradient value. Narrow strips correspond to larger values of amplitude and local density gradient perturbations than the wide ones. Small irregularities on the leading part of transient waves above and below cylinder are caused by superposing of remnants of diffusion induced boundary flows and growing transient waves. Fluid accumulated in the ahead blocking zone displaces the bands from their initial positions. In a zone far from the body initial position, the diffusion induced flows are weaker of those in vicinity of the body, and disturbances of leading part are visible only on the second strip in Fig. 3(b). Finest details in the cylinder vicinity indicate location of upstream and downstream blocked fluids and formation of boundary layers.

The body path length is reflected in the length of high gradient envelope and number of attached internal waves (the only one growing attached wave is shown in Fig. 3(b)). There are specific disturbances localized inside upstream and downstream vortices forming blocked fluid ahead of the body and vortex structure of the downstream wake.

With time the path of the body, both numbers and sizes of the blocked fluid domain and wave field domain and height of the downstream region bounded by high gradient interfaces increase. The loci of waves amplitudes maximum displace from the body surface. New horizontal high gradient interfaces are elongated from this area (Fig. 3(c)). They contact the boundaries of the wake in the vicinity of the initial position of the body. Transient disturbances inside blocked fluid ahead of the body run ahead. Small-scale vortices are observed on the downstream wake envelope. Centrals of the closed curved lines in images of internal waves indicate areas of maximum amplitude.

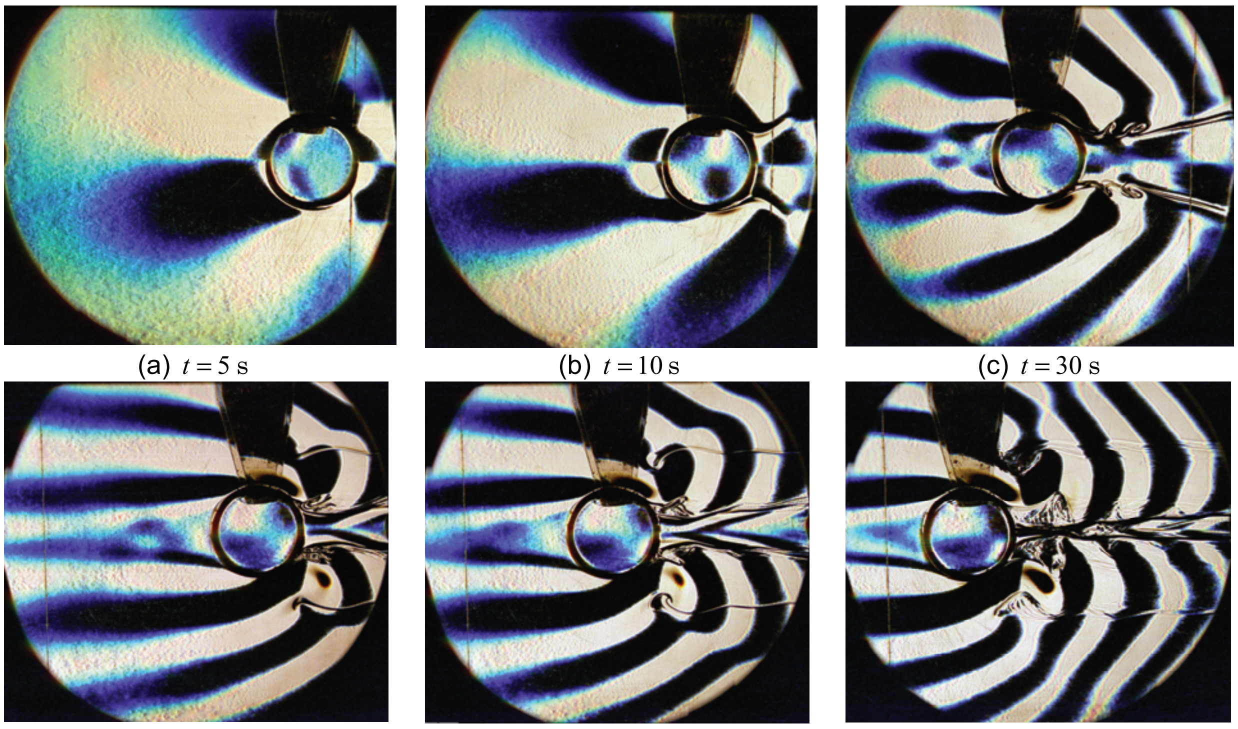

(a) $t = 5$ s (b) $t = 10$ s (c) $t = 30$ s
(d) $t = 65$ s (e) $t = 80$ s (f) $t = 195$ s

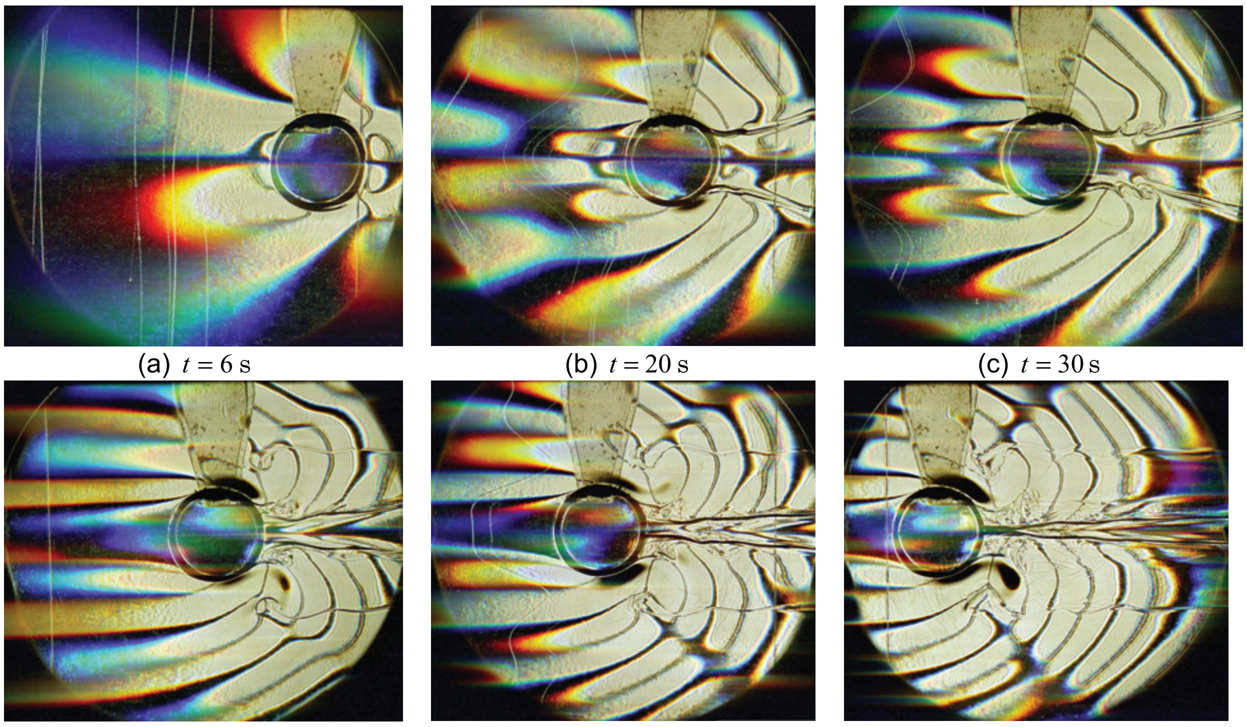
Fig. 4. Conventional schlieren images (vertical slit-Foucault knife) of flow pattern past the horizontally moving cylinder in the stratified fluid ($D = 5$ cm, $T_b = 10.5$ s, $U = 0.24$ cm/s) at different times after beginning of the motion; a-f) $-\tau = t / T_b$ = 0.48; 0,95; 2.86; 6.19; 7,62; 18.57.

Next three photos in this figure illustrate gradual formation of vortex systems on leading edges soaring interfaces. Vortices are formed in the domains of maximum wave amplitudes. Firstly, inside this area increasing of density gradient is observed (Fig. 3(d)). Then interfaces become wavy and the leading edge is transformed from thin and straight (Fig. 3(d)) into more thick and curved one (Fig. 3(e)). The sequence of arrows inside density wake in the image indicates direction of the cylinder motion. These structures are produced by the motion of the high-density gradient envelopes lines from periphery to the centre of the downstream wake. On can identify two systems of internal waves. The external one is attached waves set. Between soaring interfaces and outer boundaries of the density wake, specific wave system is located. The wavelength in this domain is defined by the vortex structure of the density wake.

Stationary pattern of flow is shown in Fig. 3(f). Transient and attached waves occupy all visible view field. The blocked fluid free of small-scale disturbances is attached to the body and moves with it. Short separated interfaces and downstream wake bounded by high gradient interfaces are placed past the body. Short internal waves associated with vortex motion propagate in the gapes between downstream wake and soaring interfaces. Vortex dipoles of the perfect form are placed on the leading edges of the interfaces. The value and direction of the local density gradient variations change strongly along any lines inside the perfect and geometrically ordered flow pattern.

Only basic flow elements are visualized by conventional schlieren method. Location of the cutting knife with respect the side of the vertical slit defines the basic colour of the image (the blue one is selected). Beginning of the motion produces anisotropic wave field, which is antisymmetric with respect to horizontal central plane (Fig. 4(a)). The length of high gradient envelopes of forming downstream wake marks the path length. The length of moving upstream disturbance ahead of the body and downstream disturbance, the latter is predecessor of the downstream wake, are different. Wave pattern contains only information about shapes of the phase surfaces, visualized by boundaries between dark (deep blue) and white strips.

After short time all basic components of the flow that are internal waves, growing upstream disturbance and downstream density wake are well outlined and distinguished. Shapes of attached waves are smooth (Fig. 4(b)). With time a sharp turn is observed on the second dark wave strip past the body, touching the domain of small scale vortices in the density wake envelope (Fig. 4(c)). Later the leading edges of the blocked fluid ahead of the body run away from the view field (Fig. 4(d)). Along the lines of the distorted phase surfaces sharp turn high gradient interface arises. The vortex pair is forming on its leading edge.



(a) $t = 6$ s (b) $t = 20$ s (c) $t = 30$ s

(d) $t = 85$ s (e) $t = 125$ s (f) $t = 180$ s

Fig. 5. Schlieren images of flow pattern past the horizontally moving cylinder in the stratified fluid ($D = 5$ cm, $T_b = 10.5$ s, $U = 0.24$ cm/s) at different times after beginning of the motion; a-f) $-\tau = t / T_b =$ 0.57; 1,90; 2.86; 8.06; 11,90; 17.14.

The interface has a shape of the internal wave trough located between the density wake and the interfaces. But the wave crests are coming to the same area from outer space. So here one can see abrupt change of the wave phase in a vicinity of the interface. Isolated black patches past the cylinder mark the domain of anomalous large amplitudes of the wave. With time both the first and the second internal waves phase surfaces are displaced on the interface. Pumping fluid propagates along the interface and fills leading edge vortex pair (Fig. 4(e)). Pattern of stabilised flow contains a set of broken phase surfaces where soaring interfaces with leading edge vortices are placed (Fig. 4 (f)). Downstream wake contains several vortex bubbles with sharp upper and lower edges. Position of these vortex bubbles is governed by the attached internal wave field. Displacement of phase surfaces near the wake is caused by strong velocity shear.

New features of the same flow are visualized by effective method 'vertical slit-thin filament in focus'. Disturbed lines in Figs. 5(a-c), (e) are density markers visualising the fluid velocity profiles. Their shapes in Figs. 5(a, b) show that transient velocity disturbance is smooth on all horizons. Formation of completely blocked fluid (deep blue band) ahead of the cylinder leads to flat part in the profile of displacements where fluid and the body velocities are equal (Fig. 5(e)).

Complex structure of upstream domain in Figs. 5(b, c) shows that there are several groups of transient disturbances running ahead during the process of liquid blocking. The latest portion of disturbances is bounded by high gradient interfaces marking the boundaries of blocked fluid (compare Figs. 5(c, d) and Fig. 3(c)). So the formation of upstream high gradient interfaces and separation points are caused by travelling ahead disturbances exactly as it happens in the downstream wake, where the separating vortices are observed. This method visualizes only lines of crests and troughs and permits to see all features of soaring interfaces and vortices on their leading edges. Black sloping lines past the cylinder confirm that the soaring vortices are placed on the lines of maximum wave displacements shown in Figs. 3(d, e).

The size of soaring vortex structure and intensity of vortex motion in this regime are small as wave amplitudes are not very large in this regime. In vicinity of dark sloping lines in Figs. 5(e, f) waves from inner region contact the waves of outer region in antiphase. At the stage of the soaring interfaces formation crests from inner wave zone and troughs from outer wave zone contact in vicinity of the soaring interfaces (Fig. 5(d)), but with time this area become more pronounced. This line can be identified in Figs. 3(e, f) as outer boundary of domain of closed elliptic isopleths, and as boundary of regular outer waves in Figs. 4(e, f). Oscillating character of soaring interfaces indicate amplitudes of vertical displacements inside wave field. Shapes of vortices immersed in the wake and formation of strong density gradient near the downstream wake central plane indicate properties of vortex motion in this region. Broken lines in the domains of intersections of waves crests and troughs and interfaces past the soaring vortex manifest existence of very narrow current and high density gradients here.

5. Conclusion

In classical fluid dynamics it is claimed that in a viscous fluid vorticity is formed near the solid boundaries and is diffused into the fluid interior. Complete classification of infinitesimal periodic motions in homogeneous fluids includes large-scale regular components and small-scale singular boundary-like components of motion (Chashechkin and Kistovich, 2004). The question what is propagating inside the fluid (regular and singular or only regular elements) is still open. Different schlieren methods demonstrate that vorticity can concentrate directly on some surfaces and lines inside continuously stratified fluids (Mitkin and Chashechkin, 1999). In these experiments the new mechanism of soaring interfaces and vortices at their leading edges formation is revealed. This mechanism acts due to non-uniform Doppler shifts of internal waves in the shear flows and non-uniform distortions of waves phase surfaces in the field of changing density gradient profiles. Mutual action of these factors lead to destruction of initially smooth surfaces of attached internal waves crests and troughs and formation of soaring discontinuities on some horizons where waves amplitudes are maximal. Interaction of waves and growing interfaces leads to accumulation of fluids in some thin layers and gradual formation of vortex dipoles on leading edges of soaring interfaces. Additional vortices are formed in some specific domains where the antiphase wave surfaces contact each other on the interface. Examples of these flow structure evolution mechanisms are presented in Figs. 3-5. Conditions of direct interactions of waves and interfaces are rather universal, and these mechanisms can act in the stratified environment where complex velocity and density profiles are observed. These mechanisms can act in the free stratified media like the far stratosphere or deep ocean with well pronounced fine structure.

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Author Profile

Yuli D. Chashechkin: He received his Eng degree in 1964 from Moscow Engineering-Physics Institute, and his Dr. of Sci. (Math and Phys) in the Institute for Problems in Mechanics of the RAS in 1981 where he is the Head of the Laboratory of Fluid Mechanics. He is a professor of the M.V. Lomonosov Moscow State University from 1987. His research interest is geophysical fluid mechanics including optic and acoustic visualisation, theory of free stratified flows.

Vladimir V. Mitkin graduated from Moscow Institute of Physics and Technology in 1995 and received his Ph.D. degree in the Institute for Problems in Mechanics of the RAS in 1998 and doctorate degree in 2004. His research interests are visualization of fluid flows and measurements of flow parameters.