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Pattern of Flow around a Sphere Oscillating an Neutrally Buoyancy Horizon in a Continuously Stratified Fluid

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

* Institute for Problems in Mechanics, RAS, prospect Vernadskogo, 101/1, 119526 Moscow, RUSSIA.
e-mail: chakin@ipmnet.ru

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Abstract : The flow pattern produced by a sphere freely sinking to the neutral buoyancy horizon in a continuously stratified liquid is visualized with different schlieren methods. Dispersion of light in the brine produces colouring of conventional schlieren images when cutting diaphragm is at the edge of blade or thread and is used to form "natural rainbow" colour schlieren image. With sensitive schlieren methods a new structural element is distinguished in the flow pattern. That is a narrow jet covered with a high gradient envelope forming in the neighbourhood of the turning points on the trajectory of the oscillating body. Due to the interaction of the body with the emitted internal waves, and also with the wake and secondary jets, the rate of amplitude damping decreases with time

Keywords: Schlieren technique, Stratified fluid, Oscillating body, Internal waves, Secondary jets.

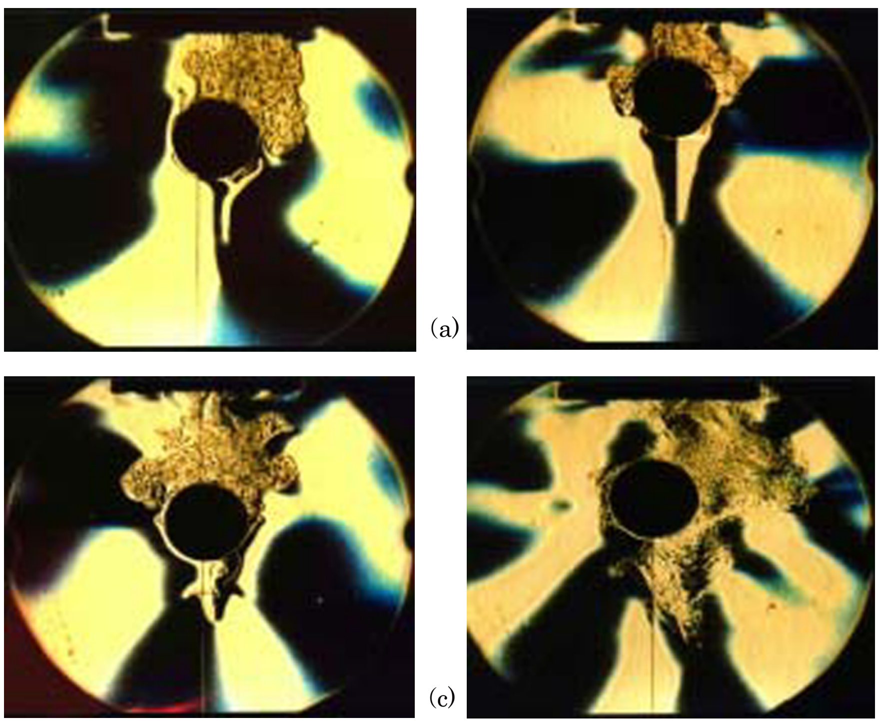
1. Introduction

Investigations of periodic and attached (lee) internal waves produced by oscillating or uniformly moving bodies are performed both theoretically and experimentally (Lighthill, 1978). Flows around a free oscillating body are studied not so well. The added mass of an oscillating spheroid in a continuously stratified fluid is calculated by Lai and Lee (1981). The generation of internal waves was studied theoretically by Larsen (1969), who experimentally registered only several first oscillations of the sphere. Levitsky and Chashechkin (1999) have registered black-and-white schlieren images of the flow pattern around a sphere free descending and oscillating in the vicinity of the neutral buoyancy horizon. They have identified new structural elements – energetic secondary jets in the vicinity of turning points of the body trajectory. The aim of this paper is to present more complete visualization of the flow around a free sinking neutral buoyancy sphere in a continuously stratified brine by using conventional and colour schlieren techniques.

2. Experiments

The experiments are conducted in $0.5 \times 0.15 \times 0.5$ m^3 and $0.7 \times 0.25 \times 0.7$ m^3 laboratory tanks with side optical windows. The tanks are filled with a stratified common salt solution by using the well-known two tanks method by Oster and Yamamoto (1963). Internal wave absorbers made from perforated plastic are mounted on the walls of the tank. The identity of the flow patterns around the body in the large and small tanks indicates that there is no perceptible interaction between the body and the free surface, walls or bottom of the tank.

Hollow, hermetically sealed plexiglass spheres of diameter 3.1, 4.5, 6.7 cm partially filled with lead shots are used as the oscillating body. For each stratification, the amount of shots is chosen so that the neutrally buoyancy level of the body is located at the centre of the field of observation. In the upper part of the tank, the gripper for releasing the sphere, without initial momentum or angular momentum, is located. The gripper consists of three point claws placed inside the hollow cylinder of internal diameter 8.0 cm and outer diameter 12 cm and is operated manually. For visualization, the IAB-458 schlieren instrument with photo and video recorders is used. The diameter of the view field is 23 cm. The conventional 'vertical slit-knife' (Vasiliev, 1968), Maksoutov's 'vertical slit-thread' and 'natural rainbow' colour schlieren method (Chashechkin, 1999) are used. The schlieren images are photographed with RFK-5 camera at frequency 1 or 2 frames per second or with a video camera.



(a) (b) (c) (d)

Fig. 1. Colour images of the convention schlieren pattern around the sphere with diameter 4.5 cm, oscillating in the stratified fluid (T_b = 7.9 s) after free sinking from the height H = 12 cm: (a)-(d) – sinking sphere, the first jet, regular and chaotic patterns of the secondary jets.

At the beginning of each run, the gripper holding the sphere is mounted in the centre of the tank at a chosen distance from the neutral buoyancy horizon. After releasing the body, it sinks freely in the fluid at rest. Its position and a pattern of induced perturbations are visualized with a schlieren instrument and registered with a camera. The experiment is repeated one hour or more after the entire dynamic and structural disturbances have degenerated.

The successive images of the flow pattern past descending and oscillating sphere produced by the conventional ‘vertical slit-vertical knife’ method are presented in Fig. 1. The boundaries between black and white strips are the crests and troughs of transient internal waves. The small-scale structures above the body are formed by the downstream wake and shedding non-stationary rear vortices. The fine interfaces in the lower part of the sphere in Fig. 1a visualize separating boundary layer. The cusp spearhead-like disturbance below the sphere in Fig. 1b is a secondary jet. The jet is formed as the result of interaction of the upstream disturbance and emitting internal waves in the neighbourhood of lower turning points of the body trajectory. The shape in this fast moving to the body jet, presented in Fig. 1, is reproduced in finest details in different experiments (compare with Fig. 1 b, c, Levitskii and Chashechkin (1999)). Past several oscillations, the sphere is surrounded by a small-scale disturbances and emitted transient internal waves (Fig. 1 d).

To illustrate the fine structure and symmetry of the secondary jet, the images produced by Maksoutov’s ‘vertical slit-thread’ method are presented in Fig. 2. The images are slightly coloured due to dispersion of the white illuminating light on large-scale disturbances. At the beginning, one

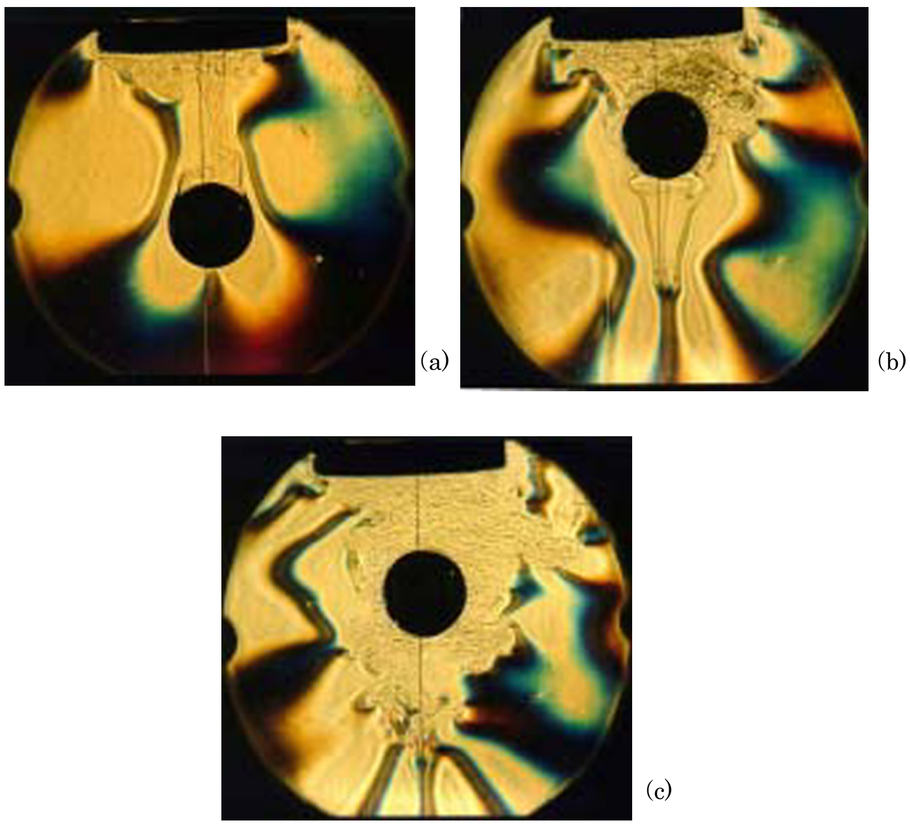


Fig. 2. Colour images of the flow pattern around the sphere (D = 4.5 cm), oscillating in the stratified fluid (T_b = 8.5 s) after free sinking from the height H = 12 cm: (a)-(c) – sinking sphere, forming first jet, decaying second jet (The visualized diaphragm is a vertical thread.)

can see disturbances around the sinking sphere and near the lower part of the gripper (black bar in the upper part of the image in Fig. 2a). The downstream wake consists of elongated fine disturbances and immersed circular rear vortices. The crest of the first half of the forming internal wave separates the image into light upper and dark low parts. The upstream disturbance below the sphere is smooth. The finest structures in Fig. 2a are rather regular and reflect weakness of all initial disturbances around the gripper, inside the wake and ahead of the sphere.

In ascending part of the trajectory past the lower turning point, the small-scale structures above the body are compressed and become more complex. The internal waves fill all the images of the flow. Below the sphere, the secondary jet of conical shape is formed. The jet, bounded by a high gradient envelope, is formed in a free space below the lowest point achieved by the sphere, moves to the body and supports its oscillations. The lower tip of the jet is a focal point of the transient internal waves generation. In this regime, the fast secondary jet loses its stability and converts into a set of small-scale vortices. These patterns are repeated successfully with every cycle of the body oscillations and every next jet below or above the sphere is longer than the previous one.

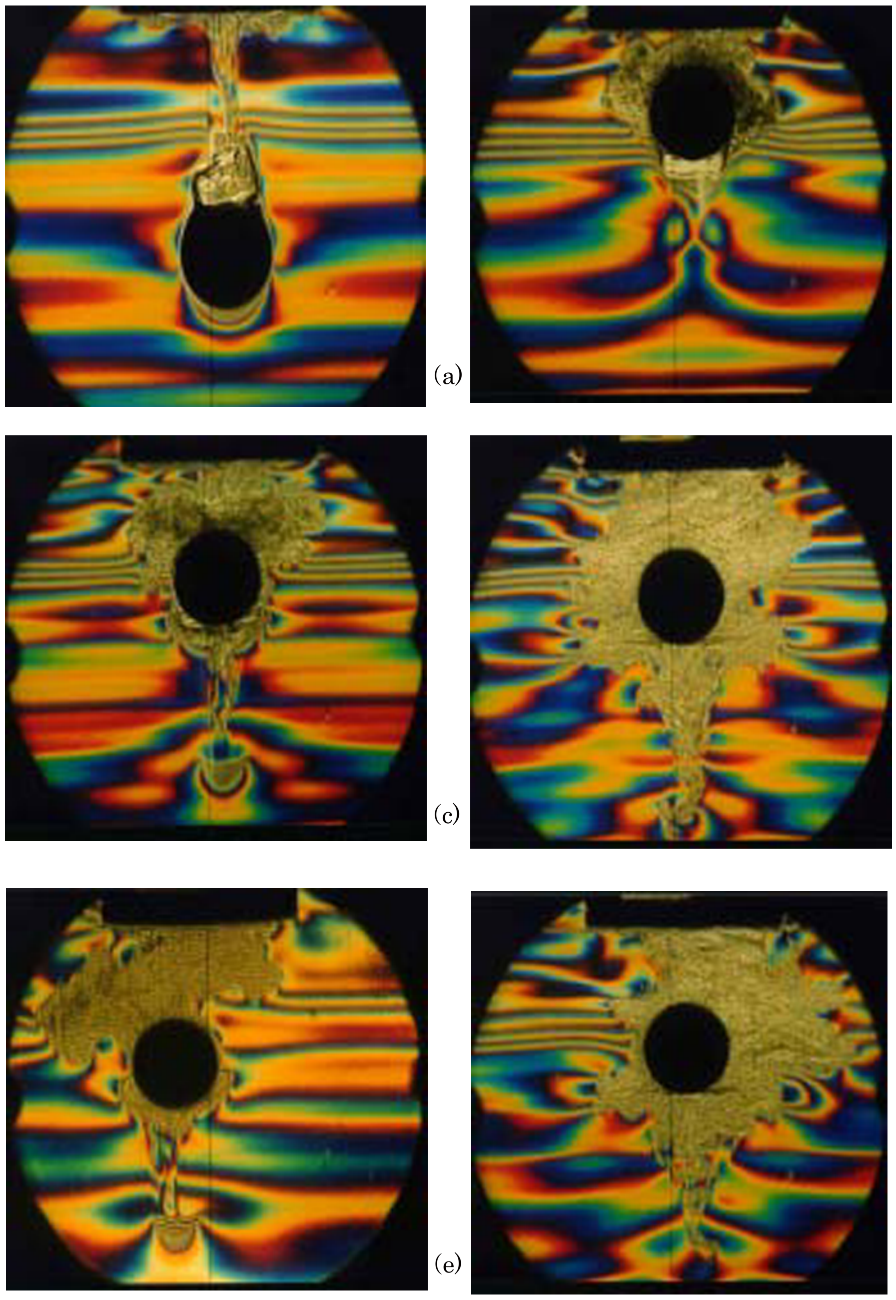
The most complete images of the flow are produced by 'natural rainbow' schlieren method (Chashechkin, 1999), which is sensitive to variations of the vertical component of the density gradient. The descending body in Fig. 3 a is covered with a thin boundary layer. There is a high gradient layer under the body, but in general the outer part of the upstream disturbances is smooth. The circular rear vortex is in contact with the downstream wake.

The initial stage of the secondary jet formation is presented in Fig. 3 b. The disturbance near the body is covered with a high gradient envelope. The circular smooth structure contacts with internal waves near the lower tip of the upstream disturbance.

The more elongated upstream secondary jet is presented in Fig. 3 c. The convexity of the lower envelope of the jet shown in the Fig. 3 c transforms into concavity with time. Subsequent jet in Fig. 3 d is longer than the previous one in Fig. 3 c. The energetic jets lose its stability and transform into a set of small-scale elements.

In Fig. 4 we have plotted the trajectory of the center of the sphere and location of lower tips of the secondary jets. Since the process is unsteady the data are given in several coordinate frames: laboratory one (l-system, z axis directed upward, and $z = 0$ on the body's neutral buoyancy horizon) and two non-inertial systems moving with the body (c-system: above the body $z_c = 0$ at the upper pole of the sphere, z_c axis directed vertically upward; below the body z_c axis directed downward at the lower pole of the sphere). The vertical coordinate is normalized on the sphere of diameter D = 4.5 cm and time is normalized on the buoyancy period, $\tau = t/T_b$, T_b=13.4 s.

The sphere performs damping oscillations around the neutrally buoyancy horizon (curve 1, l-system) and from the second oscillation, it remains above the equilibrium level. The amplitude of the first oscillations damps rather fast, then the rate of the decay decreases. The period of oscillations decreases with time. Curves 2, 11 in Fig. 4 illustrate the location of tips of the secondary jets successfully formed with time in the neighborhood of the lower turning point in the l-system (curves 2, 4, 6, 8, 10) and in the c-system (curves 3, 5, 7, 9 and 11). At the beginning of the every ascending cycle, a new jet which absorbers the traces of the previous one, is formed. Every successive jet is longer than the previous one. Its mushroom-like head is formed in a free space, occupied only by upstream disturbances and internal waves. The relative contrast of secondary jets image increases with time.



(a) (b) (c) (d) (e) (f)

Fig. 3. Colour images of "natural rainbow" schlieren image of the flow around the sphere (D = 4.5 cm, T_b = 7.9 s, H = 12 cm): (*a), (b)* – sinking and first rising of the sphere; (*c), (d)* and (*e), (f)* – forming the first and decaying the second jets (different experiments)

In Fig. 5 we have presented the time series of relative displacement of the sphere normalized on its diameter with respect to non-dimensional time. The amplitude of oscillations is proportional to the sphere diameter so normalized values of displacements practically are the same for different bodies. The period of oscillations depends on the body diameter, so the phase shift between oscillations increases with time.

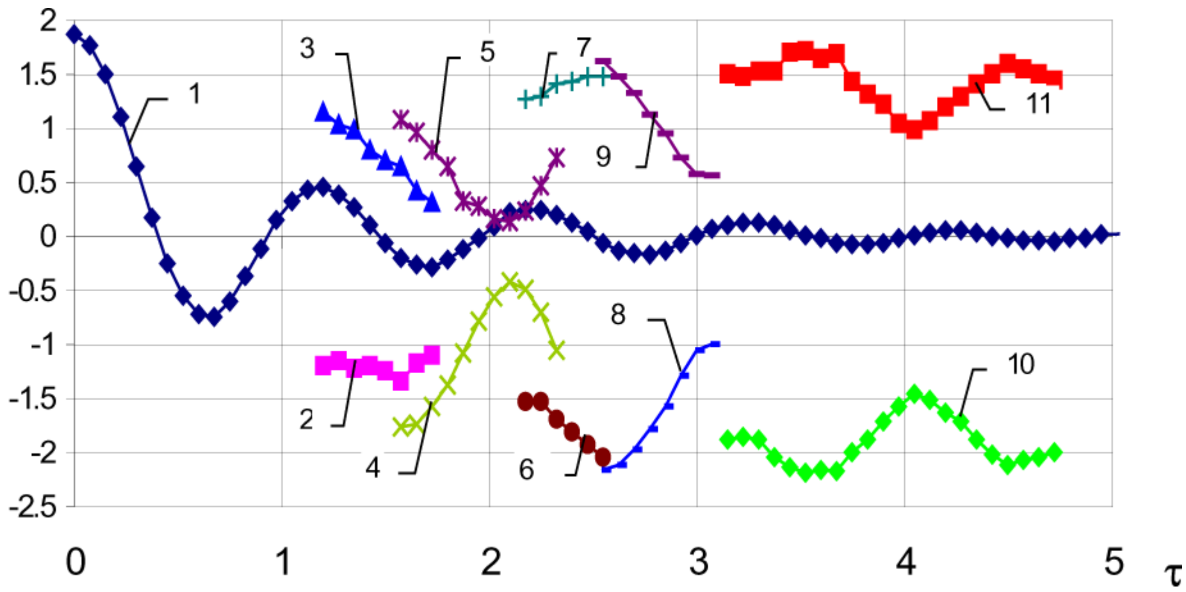


Fig. 4. Flow geometry: trajectory of the body center (1), positions of the tips of the fist, second, third, fourth and fifth jets in the *l*- and *c*-coordinate systems

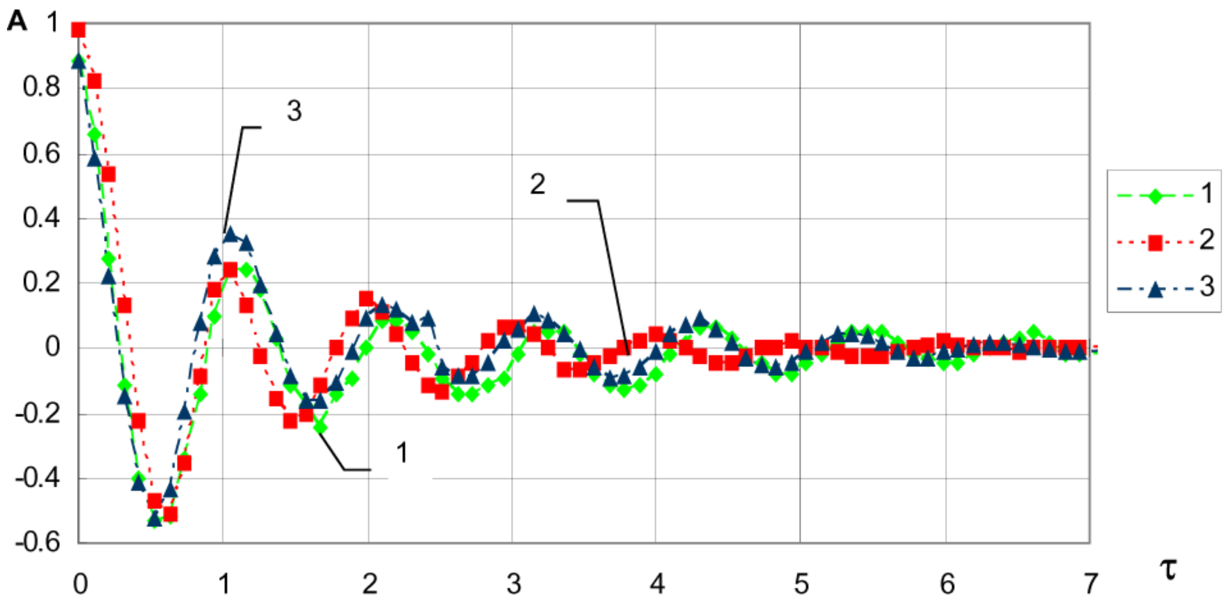


Fig. 5. Relative displacements of sphere $A = h/D$, normalized on its diameter with respect to non-dimensional time $\tau = t/T_b$ in the fluid with T_b = 9.5 s: 1-3, D = 3.1, 4.5, 6.7 cm.

3. Conclusion

The sensitive schlieren visualization shows that the pattern of a free oscillating neutral buoyancy sphere in a continuously stratified fluid flow contains the following elements: a downstream wake contacting with rear circular vortices, blocked fluid ahead of the body, a boundary layer on the body surface, emitted internal waves and extended energetic secondary jets in the vicinity of the lower and upper turning points. The high gradient envelopes bound the secondary jets.

These jets are active components of the process. Their length increases with the number of successively arising jets. At the initial stage, when the body forms a system of the secondary jets, the amplitude of oscillations decays with time rapidly. At the late stage, when the body motion is supported by the secondary jets, a rate of amplitude damping decreases.

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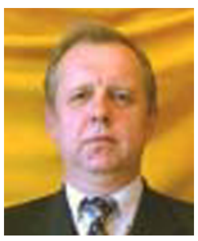
Author Profile

Yuli Dmitrievich Chashechkin: He received his Eng degree in theoretical nuclear physics 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. He worked in the Russia Metrology Service and has received current position of the Laboratory of Fluid Mechanics Head at the Institute for Problems in Mechanics in 1981. He is professor of the M.V. Lomonosov Moscow State University from 1987. His research interest in geophysical fluid mechanics includes optic and acoustic visualisation, theory of free stratified flows.



Vladimir Viktorovich Levitskiy: He received his Eng degree in testing of flying vehicles in 1978 from Moscow Aviation Institute, and his Kand. of Sci. - Math and Phys (Ph.D.) in the Institute for Problems in Mechanics of the RAS in 2001. He worked in the Russia Construction Bureau and has received current position of Senior Research Scientist in the Laboratory of Fluid Mechanics at the Institute for Problems in Mechanics in 1983. His research interest covers testing of optic visualisation instruments, experimental study of internal waves and multicomponent convection in stratified fluids.