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Review Report

Visualization of Singular Components of Periodic Motions in a Continuously Stratified Fluid

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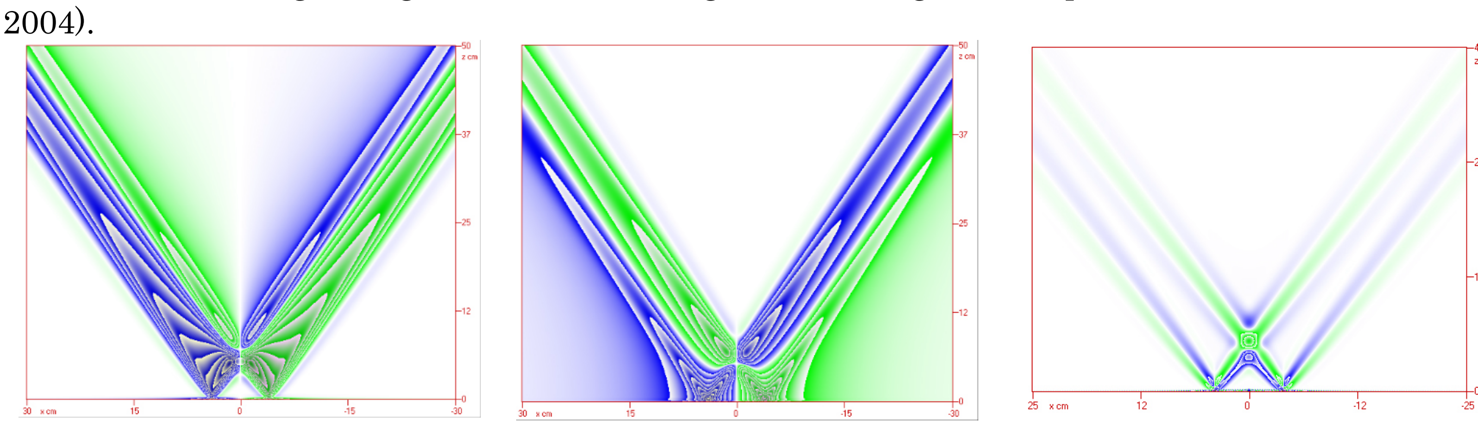
1. Introduction

Experimental studies of the waves in fluids have been a topic of interest of fundamental sciences and engineering as basis for environmental and technology applications (Lighthill, 1970). Recent investigations reveal the infinitesimal waves supplemented with a set of singular components such as boundary layer families existing on the contact surfaces and thin elongated interfaces in the fluid interior. The interfaces are stretched in the direction of source motion or energy propagation and thinned in the transverse direction. Roots of dispersion equations describe all the periodic flow components (Chashechkin and Kistovich, 2004). Non-linear interactions between reciprocal linear elements of the flows lead to formation of the new structural forms. Because of smallness of the transverse scales in singular components, high-resolution and sensitive optic instruments are used for their visualization, and Maksoutv's type techniques is one of the best. In such a way, a transverse streaky structure on a horizontally moving strip and inside its wake was visualized (Chashechkin and Mitkin, 2004). Reconnections of outer edges of the streaks result in formation of a set of symmetrical "butterfly-like" vortices gradually retransforming into conventional vortex street. Another example is a transformation of soaring interfaces within internal wave wake past a horizontal cylinder into vortex pairs and sequence of vortices (Chashechkin and Mitkin, 2006). The present study seeks to visualize singular components in the flow induced by a body oscillating periodically in a continuously stratified fluid.

2. Summation of Theory

Visualization of exact solution of classical governing equations describing infinitesimal motions of viscous exponentially stratified fluid, induced by horizontal disc, performing periodic vertical oscillations showing in Fig. 1 reveals both regular and singular components (Chashechkin et al., 2004).



(a) (b) (c)

Fig. 1. Pattern of flow in the central cross section of the conical periodic wave beam produced by a horizontal disc of radius R = 4 cm oscillating in the vertical direction ($\omega = 1\ \mathrm{s}^{-1}$, velocity amplitude U = 0.25 cm/c, T_b = 5.2 s); (a), (b) – the velocity horizontal component v_r; t = 0; 0.25 T_b and (c) – its second derivative $\partial^2 \mathrm{v}_r / \partial z^2$, t = 0.

Regular components occupy the whole space (weak phone in Fig. 1(a), (b)) and are the most profound in the wave cone sloping under the angle ϑ to horizon (here $\sin\vartheta = \pm\omega/N$, ω is wave frequency, N and $T_b = 2\pi / N$ are buoyancy frequency and period). Ratio disc diameter–to–viscous wave length scale ($L_{\nu D} = \sqrt[3]{(\nu + \kappa_s) g} / N$) defines modal structure of the beam (here ν is kinematic viscosity, κ_s is the salt diffusion coefficient and g is the gravity acceleration). The singular components are the boundary layer on emitting surface and thin envelopes of the wave cone. Transverse scales of the singular components are characterized by two universal microscales of velocity $\delta_N = \sqrt{\nu / N}$ and density $\delta_\rho = \sqrt{\kappa_s / N}$ respectively. The singular components are characterized by high levels of vorticity and rate of energy dissipation. During the wave period the envelopes are being gradually distributed across the whole beam and finally concentrated into thin edges interfaces. Outer and inner envelopes are shown in Fig. 1(a), (b) in converge phases. Locations of singular components of periodic internal waves demonstrate pattern of the second derivatives of velocity (Fig. 1(c)). While regular and singular components are emitted by the disc edge along all available directions (Fig. 1), non-linear effects are most expressed inside the conical domain located directly under the disc where the waves are intersected and the inner envelopes are converged.

3. Experimental Setup

Optical scheme of experimental setup is shown in Fig. 2. A rectangular tank *15* ($70 \times 25 \times 70$ cm^3) is filled with linearly stratified brine through the bottom valve *15* using two-bucket procedure supported by tanks *13*. The flow side view is observed by schlieren instrument IAB-458 through the optical windows *14* . Optical system (*1-12*) consist of separated illuminating and receiving parts and includes white light source *1*; condenser *2*, forming image of the light source in plane of illuminating diaphragm; lighting slit *3*; plane turning mirrors *4*, *9*, directing light rays on main spherical mirrors *5*, *8*; menisci *6*, *7* correcting aberrations; light cutting diaphragm *10* (filament, Foucault's knife or grating, forming schlieren effect), lens *11* constructing image of the flow pattern in camera *12*. Diameter of the observation field is 23 cm; the instrument spatial resolution is better than 0.1 mm).

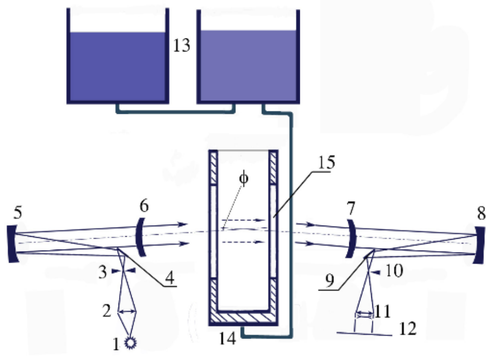
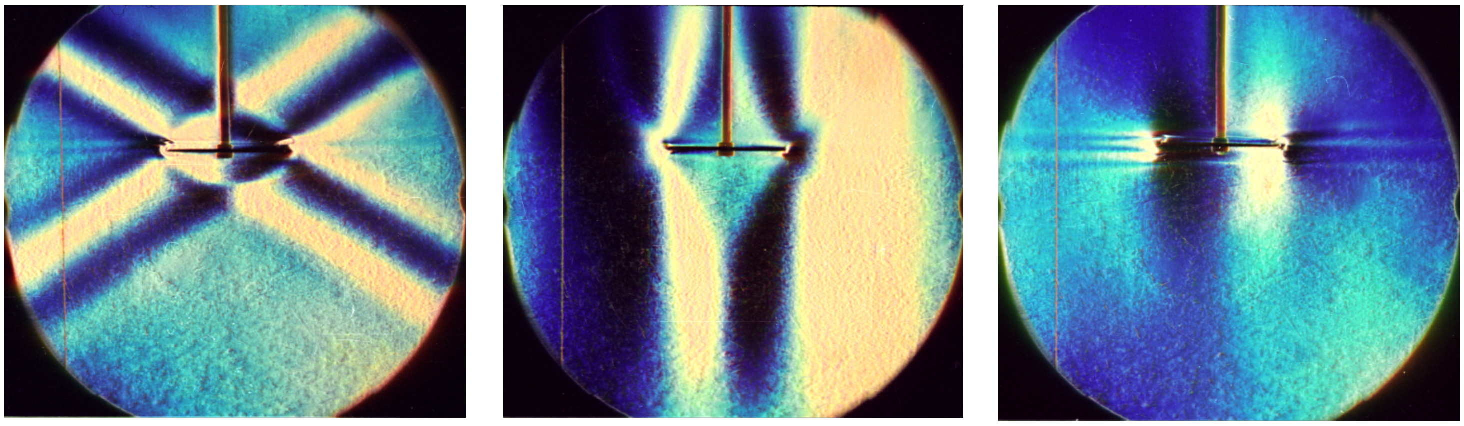


Fig. 2. Optical scheme of experimental facility.

Different periodic disturbances were produced by the vertically oscillating horizontal disc or a sphere placed in the center of the tank. A thin wire connects the disc with the crank mechanism arm driven by d.c. motor. Prior to each test, the buoyancy period was directly determined from registration of internal oscillations produced by a density marker (wake of arising gas bubble).

3. Results and Discussion

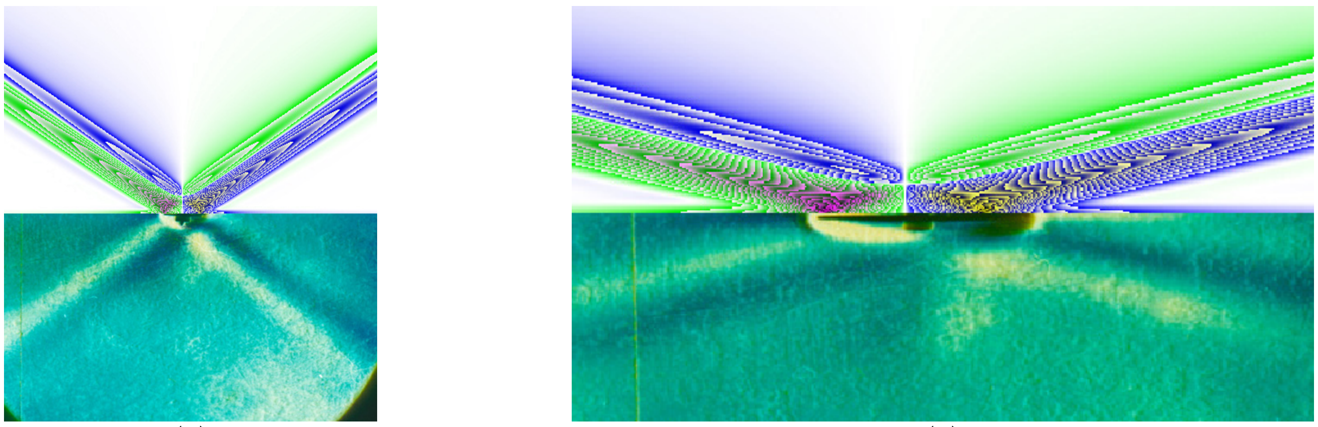
Figure 3 shows conventional schlieren images of small disturbances produced by the oscillating disc. Due to axial symmetry of the flow only central cross section is visualized. All wave beams are well outlined when $\omega < N$ (Fig. 3(a)). Images of the wave beams are antisymmetric as motions of the fluid particles occur in opposite directions above and below the disc. Right and left parts of the image in Fig. 3(a) are antisymmetric as horizontal displacements in beams occur in opposite directions. Thin horizontal strips in the central part in Fig. 1(a) represent the flows, induced by diffusion on the disc (Baydulov et al., 2005). Elliptic domain around the disc shows a near field region where non-linear effects are significant. Small edge vortex rings are formed in vicinity of the disc trajectory turning points. Internal waves crests and troughs are oriented vertically when the frequency of the disc oscillation reaches the buoyancy frequency (Lighthill, 1970). In this case the singular disturbances become weaker, and the near field region is extended in vertical direction (Fig. 3(b)). Weak secondary waves are visible in upper left part of the picture. Both regular and singular elements of fluid motions are gradually shrinking to the source if the frequency of oscillations exceeds the buoyancy frequency ($\omega > N$) and only edge vortices and diffusion induced currents still exist (Fig. 3(c)).



(a) $\omega = 0.48\ \mathrm{s}^{-1}$ (b) $\omega = 0.86\ \mathrm{s}^{-1}$ (c) $\omega = 1.2\ \mathrm{s}^{-1}$

Fig. 3. Pattern of periodic internal waves produced by vertically oscillating disc in continuously stratified brine (N = 0.88 s^{-1}, diameter of the disc is D = 5 cm, amplitude of oscillations A = 0.25 cm); a-c) $-\omega / N =$ 0.55; 0.97; 1.27.

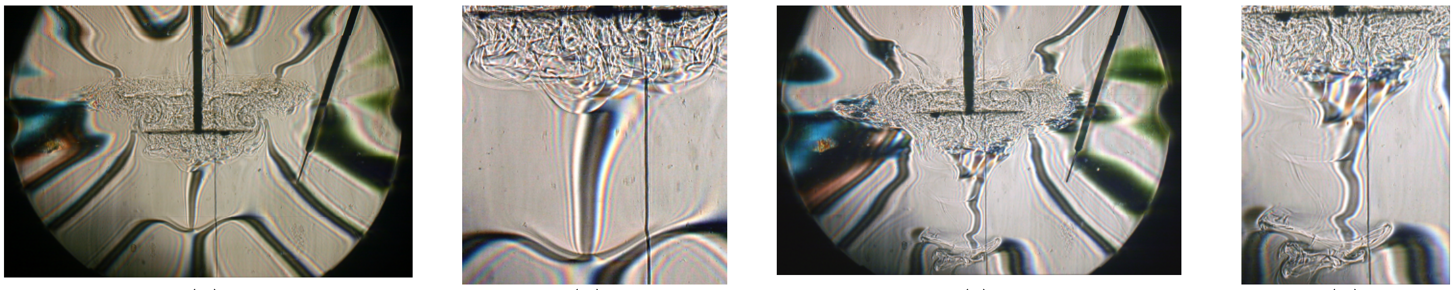
Comparisons of calculated and observed flow patterns shown in Fig. 4 demonstrate that the linear theory (Chashechkin et al., 2005) describes rather good both far field of internal waves and the near field. Slope and width of the wave cone, elliptic shape of the near field domain are distinguished in both patterns. Boundary layers are better resolved numerically than experimentally. Sensitivity of schlieren instruments near solid boundaries is decreased because of diffraction and dispersion of light effects.



(a) (b)

Fig. 4. Calculated patterns of horizontal component of velocity put above conventional schlieren images of periodic disturbances produced by vertically oscillating disc in a continuously stratified brine, T_b = 5.6 s, A = 0.25 cm; (a) – D = 2 cm, $\omega / N =$ 0.64; (b) – D = 5 cm, $\omega / N =$ 0.27.

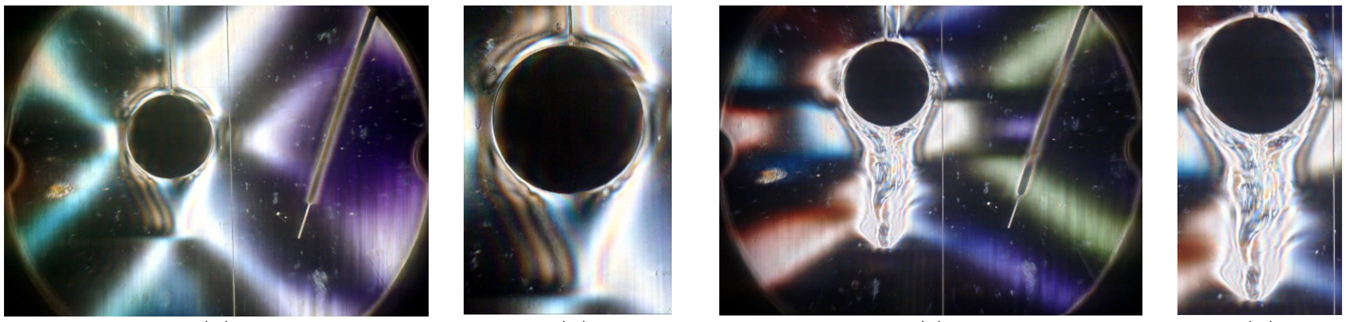
With increasing of the disc oscillations amplitude non-linear effects manifest as double extended curves in the wave field and as autocumulative jets in vicinity of the vertical axis of symmetry (Fig. 5). The central autocumulative jets have mushrooms form. They are, being the most dynamically active component of motions, formed in domains out of the layer where the disc moves due to intersections of running internal waves and blocked fluid in the near field domain. The running internal waves and double envelopes of the wave beam are reversible elements; they do disturb the initial stratification. The autocumulative jets are irreversible and bounded by thin interfaces producing "trauma of stratification" shown in Fig. 5(d). The traumas are accumulated and act as additional source of transient internal waves.



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

Fig. 5. Schlieren images of periodic flows produced by vertically oscillating disc in a continuously stratified brine $T_b =$ 7.3 s, A = 1.4 cm; (a) – D = 6.4 cm, $\omega / N =$ 0.97; (a), (c) – complete patterns of forming flow, (b), (d) – central parts of images with autocumulative jets.

Internal waves and central autocumulative jets produced by vertically oscillating sphere are shown in Fig. 6. When the amplitude of the sphere oscillations is small, the central jets are observed (Fig. 6(a), (b)). Apart from the waves cones (Fig. 6(c)), more actively oscillating sphere forms fast central autocumulative jets having a rich internal structure (Fig. 6(d)). Intrinsic time of jets existence is smaller than the wave and buoyancy periods. They move fast to and from the sphere. Additional short waves and small vortices are formed in the boundary layer on the sphere surface (Fig. 6(b), (c)).



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

Fig. 6. Internal waves and singular components produced by the vertically oscillating sphere (T_b = 11.2 s, D = 4.5 cm); a, b) – ω / N = 0.73; A = 0.5 cm; c, d) – ω / N = 0.56, A = 2.7 cm.

All regular and singular components form unique inseparable set of periodic motions. They are generated and decayed synchronously and can interact directly producing new flow components that are transient internal waves and vortices of different scales with a rich fine internal structure.

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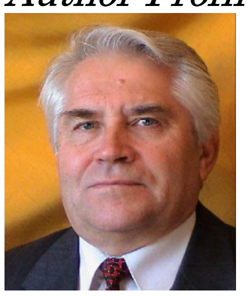
Author Profile



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