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DIRECT NUMERICAL SIMULATION OF OCEANIC FLOWS AROUND BLUNT BODIES

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Unsteady 3D separated and undulatory fluid flows around the horizontally moving blunt bodies in the ocean are very wide spread phenomena in the nature. Mathematical modeling of such flows on supercomputers give us opportunity to better understand the complex transformations of the 3D vortex structures of wake with changing of the main non-dimensional parameters (Reynolds (*Re*) and internal Froude (*Fr*) numbers). The existing experimental data give us opportunity to confirm the results of our modeling at some values of *Re* and *Fr*.

The density stratified viscous fluid flows around blunt bodies have been simulated on the basis of the Navier-Stokes equations in the Boussinesq approximation (including the diffusion equation for the stratified component (salt)) with four dimensionless parameters: $Fr = U/(N \cdot d)$, $Re = U \cdot d/\nu$, $A = \Lambda/d > 100$, $Sc = \nu/\kappa = 709.22$, where U is the scalar of the body velocity, d is the diameter of body; Λ is the buoyancy scale, which is related to the buoyancy frequency N and period T_b ($N = 2\pi/T_b$, $N^2 = g/\Lambda$); g is the scalar of the gravitational acceleration; ν is the kinematical viscosity, κ is the salt diffusion coefficient. The dimensionless density $\rho = 1 - x/(2A) + S$ where x is a vertical Cartesian coordinate, S is a dimensionless perturbation of salinity.

For solving of the Navier-Stokes equations the Splitting on physical factors Method for Incompressible Fluid flows (SMIF) with hybrid explicit finite difference scheme (second-order accuracy in space, minimum scheme viscosity and dispersion, capable for work in wide range of *Re* and *Fr* and monotonous) has been developed and successfully applied [1-2].

For the visualization of the 3D vortex structures in the wake the isosurfaces of β has been drawing, where β is *the imaginary part of the complex-conjugate eigen-values of the velocity gradient tensor* **G** (fig. 1). The good efficiency of this β-visualization technique has been demonstrated in [3-4].

The classifications of stratified viscous fluid flow regimes around a sphere [4] and a square cylinder are very different. For example, the blocking zone (BZ, fig. 3) before the sphere is absent. At the present work the refined classification of flow regimes around a sphere at $Re = 10, 100, 200, 250, 350$ are presented in a wide range of *Fr*. This classification is in a good agreement with the experiment [5].

The following classification of 2D stratified viscous fluid flow regimes around a square cylinder has been obtained by SMIF [1-2] at $Re < 200$ (fig. 2): **HC**) $Fr > 20$ – a steady symmetrical recirculation zone (RZ) with length L_0 (Re); **1RZ**) a steady symmetrical RZ with length $L < L_0$ and the internal waves (IWs); **V**) a procession of the vortices in the wake; **2RZ**) two steady symmetrical RZs before and after the square cylinder; **BZ**) a steady symmetrical BZ with the length L_b before the square cylinder (L_b is rapidly increased with decreasing of Fr) (fig. 3); **2RZU**) a procession of the vortices (bounded by IWs); **2RZS**) an unsteadiness inside RZ (with steady symmetric boundaries) and the symmetric field of IWs. This classification is in some agreement with the experiment [6].

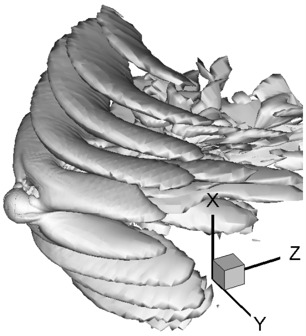

Figure 1. Vortex structures of the sphere wake at Fr = 0.5, Re = 100 (isosurfaces of β = 0.02).

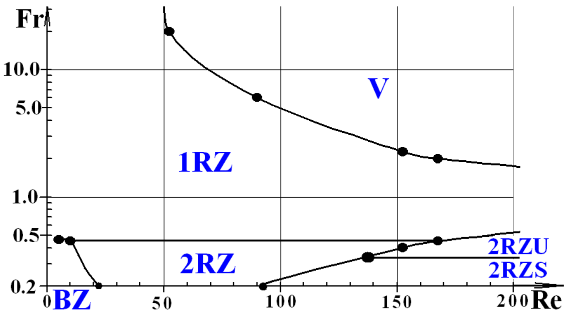

Figure 2. The classification of the regimes of 2D stratified viscous fluid flows around a square cylinder.

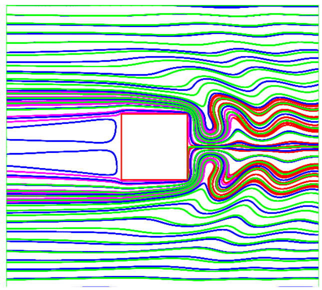

Figure 3. Stream lines around a square cylinder at Fr = 0.1, Re = 50 (two symmetrical "*hanging vortices*" in the wake).

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REFERENCES

[1] O.M. Belotserkovskii, V.A. Gushchin and V.N. Konshin. The splitting method for investigating flows of a stratified liquid with a free surface. *USSR Computational Mathematics and Mathematical Physics*, Vol. **27**, No. 2, pp. 181–191, 1987.

[2] V.A. Gushchin and V.N. Konshin, Computational aspects of the splitting method for incompressible flow with a free surface. *Journal of Computers and Fluids*, Vol. **21**, No. 3, pp. 345–353, 1992.

[3] V.A. Gushchin and P.V. Matyushin, Vortex formation mechanisms in the wake behind a sphere for 200 < *Re* < 380. *Fluid Dynamics*, Vol. **41**, No. 5, pp. 795–809, 2006.

[4] V.A. Gushchin and P.V. Matyushin, Numerical simulation and visualization of vortical structure transformation in the flow past a sphere at an increasing degree of stratification. *Comput. Math. and Math. Physics*, Vol. **51**, No. 2, pp. 251–263, 2011.

[5] Q. Lin, W.R. Lindberg, D.L. Boyer and H.J.S. Fernando, Stratified flow past a sphere. *J. Fluid Mech.*, Vol. **240**, pp. 315–354, 1992.

[6] D.L. Boyer, P.A. Davies, H.J.S. Fernando and X. Zhang, Linearly Stratified Flow Past a Horizontal Circular Cylinder. *Philosophical Trans. of the Royal Society of London. Series A: Mathematical and Physical Sciences*, Vol. **328**, No. 1601, pp. 501–528, 1989.