NUMERICAL ANALYSIS OF LARGE SCALE STRATIFIED FLOWS AROUND AN HORIZONTAL STRIP

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Abstract
A numerical investigation of the stratified flow developing around a thin horizontal plate at moderate Reynolds numbers is presented. Direct numerical simulations or Large eddy simulations based on the JETLES numerical code are compared to linearized analytical solution concerning large scale structure of the flow.

Key words: Stratified flows, Large eddy simulation, Internal waves, Wakes.

1 Introduction
The density stratification has been investigated during last years as an important topic in environmental and technological flows. Density changes lead to specific set of phenomena, especially internal and lee waves and anisotropic turbulence due to inhibition of vertical mixing by stratification [1].

A numerical model adapted from the JETLES code [2] has been developed and validated [3]-[6] from laboratory experiments [7]-[8] performed in a salty water channel at low Reynolds number exhibiting reasonable agreement with data of Schlieren visualization, density marker and probe measurements of internal wave fields. In continuation to previous work concerning a vertical strip towed in a channel, new numerical results are presented for the more delicate case of horizontal plate.

In this approach, the large scale structure of the flow is compared to a previous derived analytical solution [9] when the fine structure of the flow as introduced in [10] and occurring at high Reynolds numbers are presented in a companion paper (Y.D. Chashchkin & I.V. Zagumenny, same issue).

2 Numerical tools
In this investigation, uniform flow of a stratified fluid with density profile \( \rho(z) \), of horizontal velocity \( U \) and buoyancy frequency \( N = \sqrt{\frac{g}{\rho} \frac{d\rho}{dz}} \) past a body of characteristic dimension \( D \) is considered (equivalent to a body moving with the same speed in opposite direction in a quiescent stratified fluid).

The major dimensionless parameters governing this problem are the Froude Number \( Fr = \frac{U}{ND} \), the Reynolds number \( Re = \frac{UD}{\nu} \) and ratio of intrinsic length scales \( C = \frac{A}{D} \) (where \( A = \frac{\ln \rho}{D} \) is a stratification length scale). Ratio of dissipative coefficients defines the Schmidt number \( Sc = \frac{\nu}{\kappa_s} \) (\( \nu \) is kinematic viscosity and \( \kappa_s \) is salt diffusivity). The set of the dimensionless parameters provide conditions of numeric and small scale laboratory modeling of environmental flows.

The numerical code used herein was adapted [3-5] from the JETLES solver (courtesy of Verzicco and Orlandi [2]) to variable density flows. The second order finite difference discretization in combination with a third order Runge Kutta time marching procedure is quite efficient for fast unsteady flows at a reasonable computational cost. The 3D code has been rewritten in Cartesian mesh and equation of salinity transport has been added to account for density effects. The mean flow is assumed two dimensional, as
shown in Fig.1. The code, however, was run on a quasi 3D mode with 500 grid points in streamwise and vertical directions and 9 grid points along the cross direction in combination to periodic boundary conditions. When necessary, a Smagorinsky type closure model was introduced to resolve subgrid turbulence for large Reynolds numbers.

The numerical results for a vertical strip in stably stratified incompressible flow have been compared to another numerical approach based on two different numerical methods, using a compact finite-difference discretization. The numerical scheme itself follows the principle of semi-discretisation, with high order compact discretization in space, while the time integration is carried out by the Strong Stability Preserving Runge–Kutta scheme. Results were compared against the reference solution obtained by the AUSM finite volume method [11] and are presented in another companion paper (T. Bodnar et al, same issue).

The chosen test cases allowed demonstrating the ability of selected numerical methods to represent stably stratified flows over horizontal strip [7] and hill type 2D obstacles [8, 12] with generation of internal waves.

Here we present new computations concerning a horizontal plate following the configuration presented in Figure 1. The plate with length 40 cm, is towed in a stratified flow at rest with velocity of 0.55 cm/s. The initial stratification follows a density profile: \( \rho_0 \exp(-z/9.8) \).

\[
\begin{align*}
\frac{\partial w}{\partial x} &= 0, & \frac{\partial S}{\partial x} &= \frac{\partial \phi}{\partial x} &= 0 & \text{at } x = 0, L_x \quad \frac{\partial u}{\partial z} &= 0, & \frac{\partial w}{\partial z} &= \frac{\partial \phi}{\partial z} &= 0 & \text{at } z = 0, L_z
\end{align*}
\]

\[\rho_0(z) = \rho_{00} \exp\left(\frac{z}{\Lambda}\right)\]

Figure 1: The numerical tank and boundary conditions.

### 3 Numerical results

The Large eddy simulations have been performed by respect to the laboratory experiments in [9] for horizontal strips with different lengths. The transient numerical solution of impulsively started flow is analysed and compared to experimental data. Results are compared on Figure 2 with an analytical solution of linearized equations in combination with adapted boundary conditions. In such a way, the wave characteristics are conserved.

These results also fit qualitatively well with computations performed by Y.D. Chashechkin & I.V. Zagumenny, (same issue) concerning the wave field, when the far field is altered in the analytical solution due to necessary artificial boundary conditions.
Figure 2: Vertical velocity isolines from numerical simulation (top) and analytical solution (bottom).

D = 40 cm, Tb = 6.28 s, U = 0.55 cm/s, Re = 2200, Fr = 0.014

4 Conclusions

The developed numerical code proved to be adapted to the resolution of large structures occurring in stratified flows. Due to good level of discretization and order of resolution, it allows to undertake numerical simulations of real environmental flows with a good accuracy and a reasonable computational cost.

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References


