Parallel Computing of 3D Separated Homogeneous and Stratified Fluid Flows around the bluff bodies

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The understanding of the dynamics and kinematics of the 3D unsteady separated homogeneous and stratified viscous fluid flows around the bluff bodies is very important both from theoretical and from practical point of view. The laboratory investigations of such flows are difficult and in some cases impossible. With the development of high-performance computers and especially cost effective massive parallel computers with a distributed memory the numerical simulation becomes one of the more effective approaches for such investigations. At the present paper for the investigation of the 3D unsteady separated homogeneous and stratified viscous fluid flows around the bluff bodies (sphere and 3D circular cylinder) at $200 \le Re \le 1000$ the direct numerical simulation is used. ($Re = Ud/\nu$, where U is the free-stream velocity, d is the diameter of the sphere or cylinder, and ν is the kinematic viscosity). For this simulation the Splitting on physical factors Method for Incompressible Fluid flows (SMIF) with hybrid explicit finite difference scheme (second order of accuracy in space, minimum scheme viscosity and dispersion, capable for work in wide range of Reynolds numbers and monotonous) based on Modified Central Difference Scheme (MCDS) and Modified Upwind Difference Scheme (MUDS) with special switch condition depending on velocity sign and sign of first and second differences of transferred functions was developed and successfully applied [1-2]. Some applications of SMIF for solving of different problems are described in [3]. The Poisson equation for the pressure was solved by the Preconditioned Conjugate Gradients Method. The parallelization of the algorithm was made and successfully applied on massive parallel computers with a distributed memory such as PARAM 10000 (based on Ultra Sparc II processors (400 MHz) with Paramnet) and MBC 1000M (based on the processors Alpha21264 (667 MHz) with Myrinet 2000).

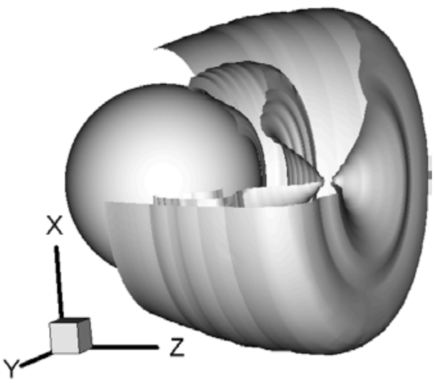

Fig. 1. *Re*=200. Vortex structures (the zero isosurface of the second eigenvalues of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor).

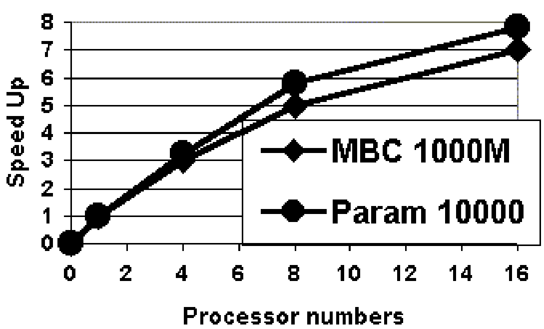

Fig. 2. Comparison of the speed ups for Paramnet (Param 10000) and Myrinet 2000 (MBC 1000M).

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For the investigation of the 3D unsteady separated homogeneous viscous fluid flows around the sphere the spherical coordinate system (O-type grid) is used: $x= r \sin\theta \cos\varphi$, $y= r \sin\theta \sin\varphi$, $z= r \cos\theta$, where z, x, y are streamwise, lift and lateral directions, accordingly. The following number of grid points (r, θ, φ) is used: (120 x 60 x 120) (see Fig. 1). The number of grid points in the boundary layer in radial direction is 10. The vortical regions for Re=200 in the Fig.1 were identified by using the definition of vortex core as a connected region containing two negative eigenvalues of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor (where the rate of strain $\mathbf{S}_{i,j}$ and rate of rotation $\mathbf{\Omega}_{i,j}$ tensors are $\mathbf{S}_{i,j}=(u_{i,j}+u_{j,i})/2$, $\mathbf{\Omega}_{i,j}=(u_{i,j}-u_{j,i})/2$) [4]. (In Fig. 1 one quadrant of the vortex structure was cut away in order to see the sphere surface.) Jeong and Hussain [4] provide number of examples to illustrate the advantages of this definition of vortex core over others, indicating a more robust and precise elucidation of the vortex regions.

The code was parallelized by using a domain decomposition in radial direction. We divided the computational domain into spherical subdomains corresponding to the parallel processor units. The Speed Ups for PARAM 10000 (based on Ultra Sparc II processors (400 MHz) with Paramnet) and MBC 1000M (based on the processors Alpha21264 (667 MHz) with Myrinet 2000) are practically same (see Fig. 2). This comparison was made for Re=500 on the grid 80x50x100 ($150.17<t<150.67$, dt=0.0004). This calculation on the one processor takes 55 minutes for PARAM 10000 and only 19 minutes for MBC 1000M.

At the present paper the classification of the 3D separated homogeneous viscous fluid flow regimes around the sphere at $200 \le Re \le 1000$ was refined. For $20.5 \le Re \le 270$ the separated fluid flows around a sphere are steady. For $20.5 \le Re \le 200$ the axisymmetrical separated fluid flows around a sphere was observed (see Fig. 1). For $200 < Re \le 270$ the main axisymmetrical bubble is deformed through a normal bifurcation in more topologically stable form (double-thread wake, Fig. 3). (In Fig. 3 (right) a half of the vortex structure was cut away in order to see the sphere surface.) These flows are characterized by the existence of non-zero lift/side and torque moment coefficients [5].

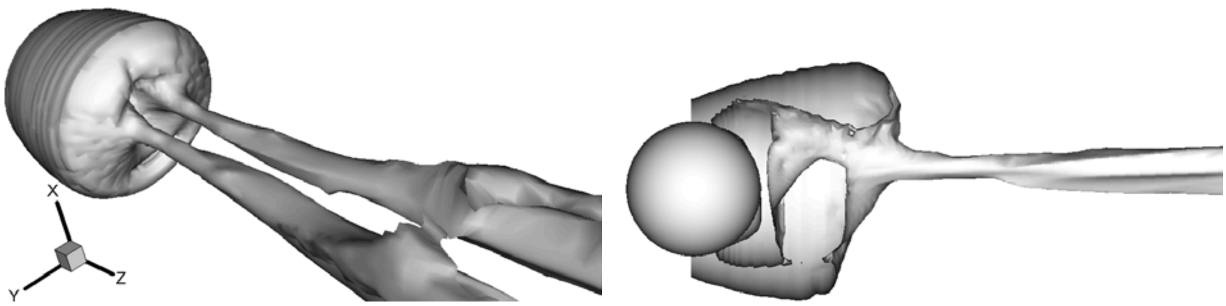

Fig. 3. Re=250. Vortex structures (the zero isosurface of the second eigenvalues of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor): oblique view (left) and view in the wake symmetry plane.

For $Re > 270$ the separated fluid flows around a sphere are unsteady and periodical. For $270 \le Re < 400$ the wake becomes unsteady through a Hopf bifurcation and periodical separation of the hairpin-shaped vortices is observed only from one part of the sphere surface (see Fig. 4), and the time-averaged lift/side and torque moment coefficients are not equal to zero. Besides for $360 \le Re < 400$ the regular rotation of the wake is observed (Strouhal numbers corresponding to this rotation are St_{rot}=0.0044, 0.0058 for Re=375, 380 accordingly). ($St_{\mathrm{rot}} = f_{\mathrm{rot}}d/U$, where f_{rot} is the rotation frequency.)

For $400 \le Re \le 600$ the periodical separation of the hairpin-shaped vortices is observed from opposite parts of the sphere alternatively, and the time-averaged lift/side coefficients of such flows are equal to zero (see Fig. 5). For $Re > 600$ the irregular rotation of the wake is observed (see Fig. 6). The Strouhal numbers:

St=	0.133,	0.140,	0.145,	0.141,	0.182,	0.174,	0.193,	0.135,	0.112,	0.142
for Re =	280,	290,	300,	350,	360,	375,	380,	400,	500,	600

correspondingly are in a good agreement with experiment [6] ($0.15 < St < 0.2$) and other experimental and numerical results (in [7] St=0.137 for Re=300). ($St = fd/U$, where f is the shedding frequency.)

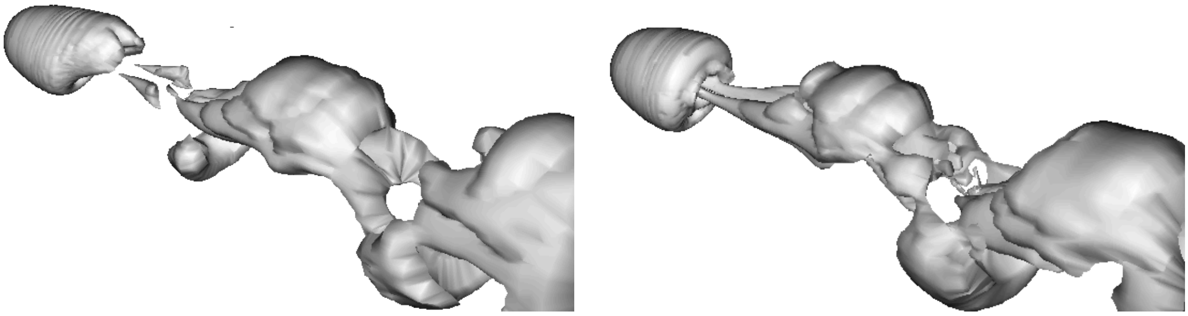

Fig. 4. *Re*=300. Vortex structures (the zero isosurface of the second eigenvalues of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor): t=775 (left), t=782.

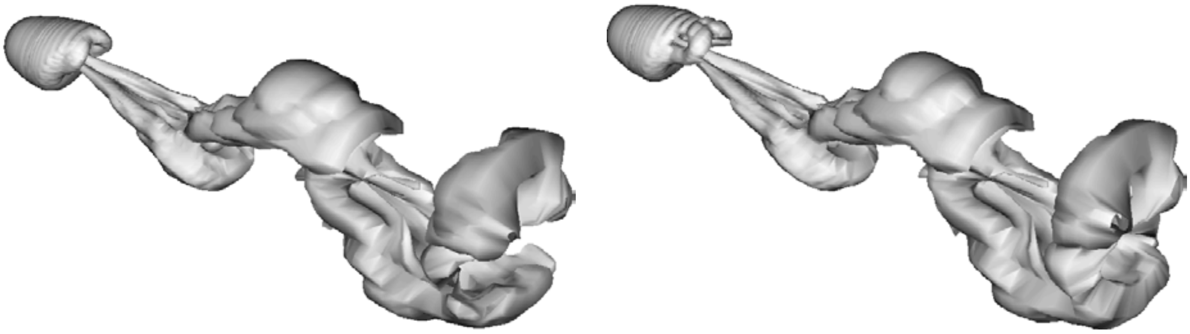

Fig. 5. *Re*=400. Vortex structures (the zero isosurface of the second eigenvalues of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor): t=334 (left), t=335.

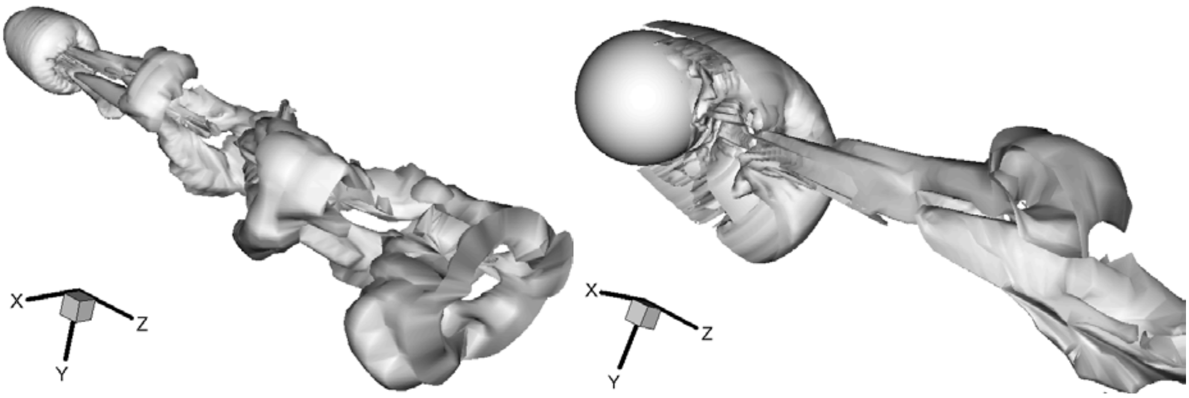

Fig. 6. *Re*=700, t=570. Vortex structures (the zero isosurface of the second eigenvalues of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor): oblique view (left) and view in the plane of section of the wake.

Transitional regimes of separated homogeneous fluid flows around a 3D circular cylinder were obtained for $200 \le Re \le 400$. For $200 \le Re \le 300$ obtained periodical 3D flows are corresponding to known mode A (with periodical structures along the axis of a cylinder equal to $3.5d \le \lambda \le 4d$, where d is a diameter of a cylinder) (see fig. 7). The regime with large dislocations previously discovered in experiments was obtained numerically for $210 \le Re \le 260$. For $300 \le Re \le 400$ obtained periodical structures have length $0.8d \le \lambda \le 1.0d$ approximately, what is in agreement with known mode B (see fig. 8). The values of the maximum phase difference along the span are approximately equal to 0.1T (for mode A) and 0.02T (for mode B), where T is the period of the flow. For Re = 300 obtained both modes A and B are existing simultaneously.

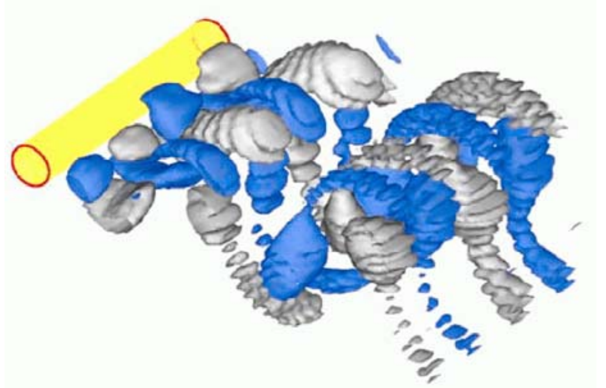

Fig 7. Isosurfaces of the projection of the vorticity on the *x* axis. Mode A, *Re*=230, L=7.5D.

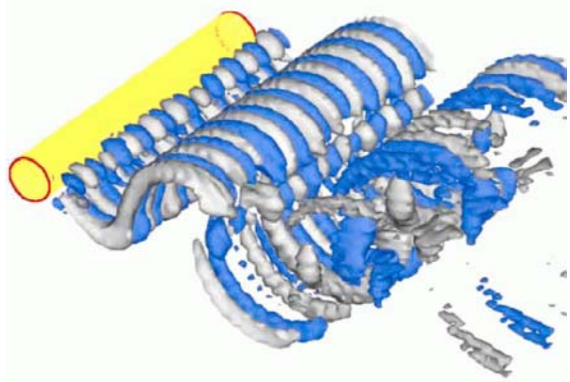

Fig. 8. Isosurfaces of the projection of the vorticity on the *x* axis. Mode B, *Re*=320, L=7.5D.

The separated stratified fluid flows around a 2D circular cylinder for some range of Reynolds and Froude numbers ($20.25<Re<113.5$, $0.13<Fr<0.73$) were calculated. All the peculiarities of stratified flows around a circular cylinder were modeled with a good accuracy: internal waves behind an obstacle, blocked liquid area before it, the size of this area increased with Froude number decreasing.

Acknowledgements

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