The PHYSALIS Method for Disperse Particle-Fluid Flows

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PHYSALIS is a method for the direct numerical simulation of fluid flows with suspended particles. Although not an immersed boundary method in the ordinary sense, it shares a number of similarities with that approach.

The method, described in detail in Zhang & Prosperetti (2005), is rooted in the simple observation that, due to the no-slip condition, the velocity of the fluid exactly matches that of the particle on the latter's surface. Near the surface, therefore, the difference between the fluid and the particle velocity is small, which permits a linearization of the Navier-Stokes equations about the velocity of the particle surface. After a simple transformation, the resulting equations are formally equal to the Stokes equations a closed-form solution of which can be expressed in terms of a series with unknown coefficients for bodies with a simple shape such as spheres and cylinders. By matching this expression to a conventional finite-difference solution valid away from the particle surface, a composite solution is obtained consisting of the analytic solution in the layer of cells adjacent to the particles and of the finite-difference solution farther away (figure 1, left).

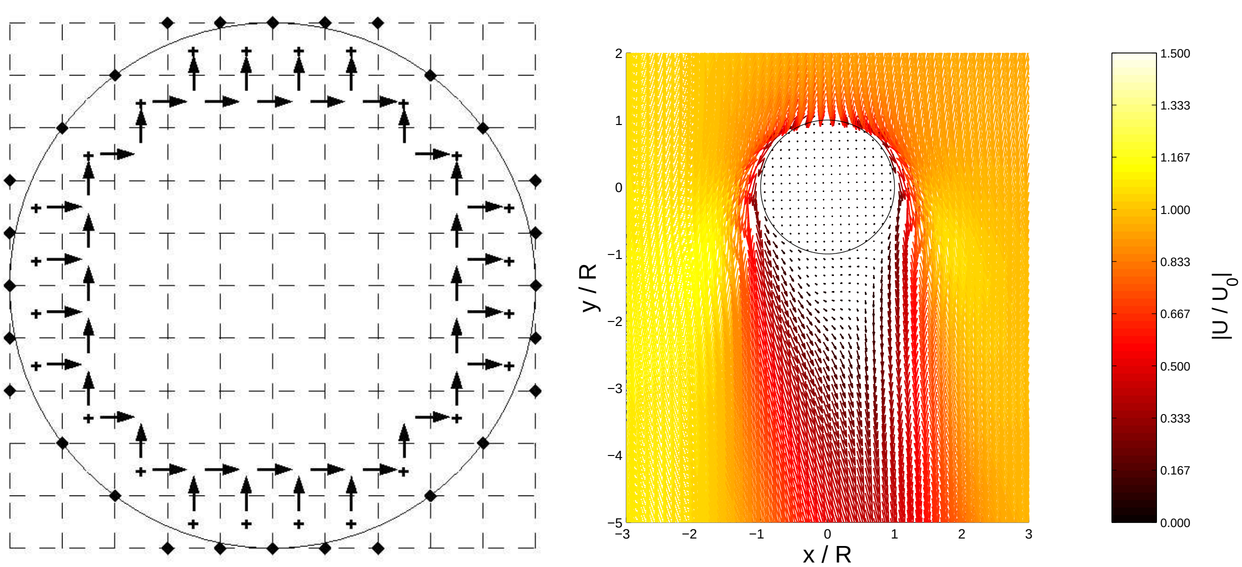

Figure 1: *Left*: Illustration of the matching procedure of the analytic and finite-difference solutions in two dimensions. The analytic pressure and vorticity fields are equated to those obtained from a provisional finite-difference solution at a number of discrete points (crosses and diamonds). By solving this over-determined system, an approximation to the analytic coefficients is found. The analytic solution with these coefficients is then used to assign velocity values at the velocity nodes (arrows), which are then used as boundary conditions for the finite-difference solution and so on until convergence.
Velocity field in the symmetry plane for the flow around a sphere immersed in a fluid in solid body rotation (left) and a higher-resolution close-up (right). The length of the arrows, which are color-coded, is proportional to the velocity. The Reynolds number is $2RU_0/\nu = 50$ and the dimensionless angular velocity of the solid body rotation $2R\omega/U_0 = 0.1$; U_0 is the undisturbed incident velocity at the sphere center and R the radius of the sphere (from Bluemink et al. 2008).

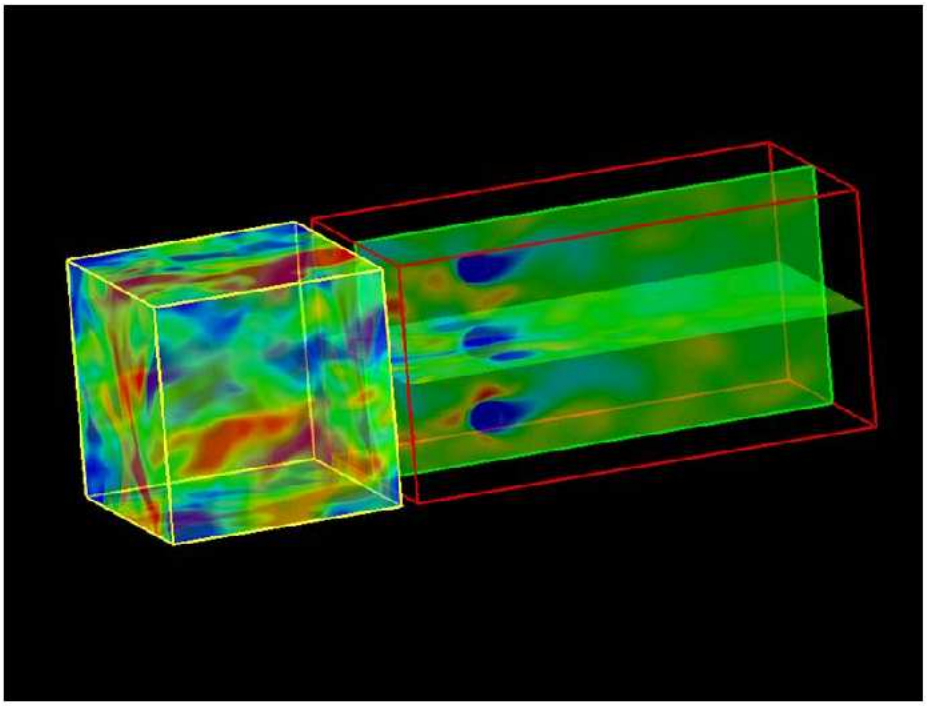

Figure 2: Homogeneous turbulence generated in the cube on the left is convected wiuth a uniform velocity past 5 spheres arranged in a plane perpendicular to the mean flow.

The method offers a number of advantages: (1) the matching of the two solutions is effected on a Cartesian grid, thus avoiding the geometrical complexity arising from the mismatch between the particle boundary and the grid; (2) as the number of degrees of freedom by which each particle is described – namely the coefficients of the series is increased, the error decreases spectrally, rather than algebraically; (3) the no-slip condition at the particle surface is satisfied exactly; (4) the fluid-dynamic force and couple acting on the particle equal the low-order coefficients and therefore are obtained directly, thus avoiding the need to calculate the fluid stress at the particle surface and integrating it.

After a description of the method, a number of examples will be shown and discussed: (1) lift and drag on one and two spheres in a fluid in solid-body rotation (see figure 1, right); (2) turbulent flow past several fixed spheres (figure 2); (3) gravitational settling of 1.024 spheres; (4) acoustic scattering by 512 cylinders.

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