Efficiently Modeling Viscous Flow Effects by means of Regularization Turbulence Modeling and Local Grid Refinement

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In offshore applications, details of viscous flow effects can become relevant when predicting e.g. drag forces on the pillars of oil drilling rigs or sloshing modes in drilling holes in floating production units. This motivates a novel approach for efficiently simulating viscous flow effects at high Reynolds numbers with the CFD simulation tool ComFLOW.

In ComFLOW, the Navier–Stokes equations can be solved for one-phase and for two-phase flow. The governing equations are discretized on a staggered Cartesian grid, the discretization being second-order in space. For time integration a second-order Adams-Bashforth time integration scheme is used. An improved Volume-of-Fluid (IVOF) algorithm is used for free-surface displacement [2, 4].

Modeling the details of viscous flow effects in high Reynolds number flows requires: (i) a *regularization* LES turbulence model, (ii) *modeling of the wall-shear stress* accounting for an underresolved turbulent boundary layer, and (iii) *local grid refinement* to locally achieve a high grid resolution in a computationally efficient manner.

1 Modeling Turbulence

A novel approach to modeling large scale features of turbulent flow is presented by the class of *regularization* turbulence models [5]. The convective term $\mathcal{C}(\mathbf{u},\mathbf{u}) = \mathbf{u}\cdot\nabla\mathbf{u}$ creates ever smaller scales of motion (the forward energy cascade) until the smallest scales are dissipated by diffusion. A family of regularization models exist that restrain the production of ever smaller scales, while preserving the skew-symmetry of the original convective term. The skew-symmetry is responsible for the conservation of (among others) energy, which is crucial for a correct prediction of large scale features in the flow. In our implementation, the convective term $\mathcal{C}(\mathbf{u},\mathbf{u})$ is replaced by $\overline{\mathcal{C}(\overline{\mathbf{u}},\overline{\mathbf{u}})}$. The bar denotes a filter operation over a filter length of the order of the grid size. This regularization model is (in terms of the filter length) a second-order accurate approximation of the original convective term.

In its current implementation, the regularization model is stabilized by a model that adds a minimal amount of eddy viscosity [6]. It is part of our future plans to improve the discrete filter, which is expected to reduce the need for such a stabilization.

The presence of the turbulent boundary layer is accounted for by the Werner-Wengle boundary layer model [7]. In this model the universal boundary layer velocity profile is approximated such that the effective wall shear stress can be computed efficiently.

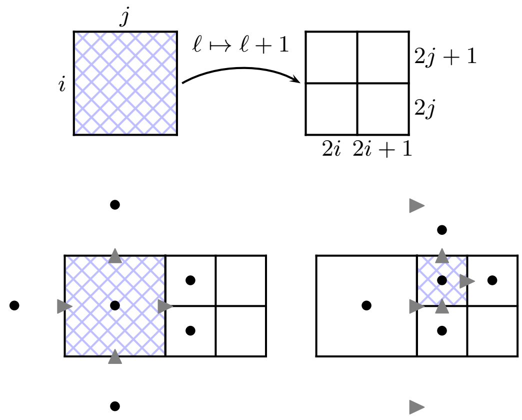

Fig. 1: Two-dimensional illustration of semi-structured grid indexing (*up*) and the discretization stencil for cells near refinement interfaces (*down*)

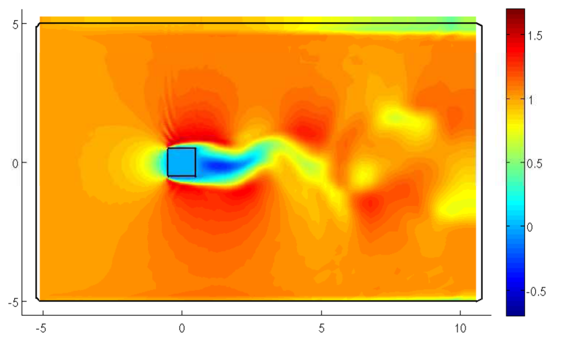

Fig. 2: Snapshot of the horizontal velocity field (flow from left to right) around a square cylinder at Re = 10,000 obtained by a simulation with the stabilized regularization model.

2 Local Grid Refinement

High grid resolution is essential for sufficiently resolving the production and development of turbulence around and behind an obstacle. Typically stretched grids introduce unnecessary refinement in regions of less interest. Therefore we pursue the approach of (Cartesian) local grid refinement, which provides an efficient and economic tool for capturing more details in areas of interest.

A semi-structured approach is followed in which a cell (i, j, k) at refinement level ℓ is *replaced* by a set of 8 smaller cells at refinement level $\ell+1$ having indices $(2i+m, 2j+n, 2k+p)$ at offsets $m, n, p \in \{0, 1\}$. On block-shaped refinement regions the method is locally structured, hence the computational efficiency of the original array-based solution methods can be exploited as much as possible. Only at the boundaries of the refinement regions where the actual refinement takes place a new treatment is required. For describing the grid layout an auxiliary array is introduced storing only one integer for each potentially occuring cell $(i, j, k; \ell)$ pointing at the memory location of the subgrid in which it is contained [1]. Altogether a data structure results that allows for fast access to neighbouring grid cells.

A compact numerical scheme is used (following ideas presented in [3]) for the discretization of the divergence and pressure gradient operator near refinement interfaces. Because symmetry properties are maintained as well, the pressure Poisson system is solved efficiently using the existing Poisson solver of ComFLOW[4].

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