Large eddy simulation of flow over a porous surface with a parallel and adaptive lattice Boltzmann method

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Abstract

We present the inner workings of our self-developed dynamically adaptive lattice Boltzmann software AMROC-LBM and apply the code to large eddy simulations that investigate the thickening and perturbance of turbulent boundary layers over rough and permeable surfaces. Besides the fluid mechanical results, the computational performance on large-scale and massively parallel supercomputer systems is also discussed.

Keywords: lattice Boltzmann, LES, adaptive mesh, boundary layer flow.

1 Introduction

A shear flow over a flat surface develops a boundary layer. If the surface has a rough and permeable structure, the boundary layer can be altered quite considerably. For example, a turbulent flow over a partially porous wing can exhibit reduced drag because of that. A lack of understanding of the detailed fluid mechanics of such phenomena makes high-resolution direct numerical simulation (DNS) and large eddy simulation (LES) of turbulent flows over prototypical rough surface patches an interesting topic of computational fluid dynamics (CFD) research.

Predicting turbulent flows over complex porous surfaces accurately requires a low-dissipation computational approach with high temporal and spatial fidelity. While compressible LES in the transonic and supersonic regime is best accomplished with high-order finite volume schemes, the lattice Boltzmann method (LBM) has emerged as a particularly powerful alternative for LES or DNS of subsonic flows. By employing a time-explicit streaming and collision algorithm on a Cartesian grid, the LBM exhibits the properties of a conventional, Navier-Stokes-based scheme for weakly compressible flows; yet, computing times on uniform grids are easily reduced by two orders [1].

Being a type of immersed boundary method, the LBM is also well suited for effectively modelling porous structures. A unique capability of our LBM implementation is the seamless integration into a fully parallelized block-structured adaptive mesh refinement algorithm implemented in our generic parallel framework AMROC [2], thereby allowing local resolution increases on-the-fly and depending on the local flow field. In this paper, we sketch the inner workings of AMROC-LBM [3-6] and report on first LES results of boundary layer development over a prototypical rough wall scenario consisting of regularly arranged spheres of identical size [7]. Parallel performance is also discussed.

2 Methods

The LBM is based on solving a simplified Boltzmann equation for partial density distribution functions $f_\alpha(\mathbf{x},t)$ that are associated uniquely to transport in a discrete lattice velocity direction $\mathbf{e}_\alpha$. The discrete lattice Boltzmann equation reads:

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\Delta t, t+\Delta t) = f_\alpha(\mathbf{x},t) + \omega_L \Delta t \left(f_\alpha^{eq}(\mathbf{x},t) - f_\alpha(\mathbf{x},t) \right)$$

Different equilibrium functions can be used in the right-hand collision of the latter equation. For instance, for the choice

$$f_\alpha^{eq}(\rho,\mathbf{u}) = \rho t_\alpha \left[1 + \frac{\mathbf{e}_\alpha\mathbf{u}}{c_s{}^2} + \frac{(\mathbf{e}_\alpha\mathbf{u})^2}{2c_s{}^4} - \frac{\mathbf{u}^2}{2c_s{}^2} + \underline{\frac{(\mathbf{e}_\alpha\mathbf{u})^3}{2c_c{}^6} - \frac{(\mathbf{e}_\alpha\mathbf{u})\mathbf{u}^2}{2c_s{}^4}} \right] + O(\mathbf{u}^4),$$

with coefficients t_α determined from the specific discrete velocity set, it can be shown that for vanishing Knudsen number the LBM recovers the weakly compressible Navier-Stokes equations [8]. Note that considering the underlined terms in the last equation corresponds to an extended 3rd order scheme that is stable for Mach numbers up to ~0.4. Kinematic viscosity ν and collision frequency are connected in above LBM through the relation

$$\omega_L = c_s{}^2/(\nu + \Delta t\, c_s^2/2).$$

While the above method is sufficient for laminar flows, it is mandatory to apply a turbulence model in high Reynolds number situations. We adopt an LES approach with eddy viscosity model [9]. The subgrid scale turbulence is considered by adding a turbulent eddy viscosity ν_t and utilizing the effective viscosity $\nu^*=\nu+\nu_t$ in the last equation to adjust the local collision frequency. Here, we have used the constant coefficient Smagorinsky model to evaluate ν_t.

Our LBM is implemented on Cartesian meshes and considers geometrically complex boundaries with a level-set-based ghost-fluid-type approach. Dynamic mesh adaptation is applied in addition in order to increase the local resolution based on the level set function and features detected in the flow field, as provided by out MPI-parallelized structured adaptive mesh refinement (SAMR) software system AMROC.

In the SAMR approach, cells are clustered with a special algorithm into non-overlapping rectangular grids. The grids have a suitable layer of halo cells for synchronization and applying inter-level and physical boundary conditions. Refinement levels are integrated recursively. See [2] for details. The spatial mesh widths and the timestep are always refined by the same factor, which is ideal for the time-explicit LBM. Distributions streaming across refinement boundaries during the recursive temporal update are fully considered in AMROC-LBM by a specially designed correction algorithm [3-6]. For mesh partitioning, AMROC uses a space filling curve algorithm.

3 Results

An adaptive LBM-based LES of the boundary layer flow over a prototype porous surface using AMROC is shown in Fig. 1. Only two levels of dynamic mesh resolution have been used in this preliminary computation. Inspired by a case studied by Stoesser et al. [7], flow of air imposed by a flume at velocity of U=8m/s, modelled as a surface sliding in the x-direction at the top domain boundary, passes over two layers of 18 x 10 regularly positioned spheres of D=12mm diameter on top of a flat fixed wall bottom (x-y-plane). The distance of the flume is H=41mm above the sphere surfaces, giving a Reynolds number of the bulk channel flow of Re=UH/ν=20372. Figure 1 is depicting the instantaneous velocity in the x-direction after approximately 12 flow periods through the domain, when the boundary layer is reasonable well formed. Turbulent vortex structures near the rough surface, interacting and thickening the boundary layer, are well exposed by an additional isosurface (blue). Figure 2 shows the averaged x-velocity above the spheres in locations of minimal and maximal porosity for the LBM computation compared to the reference data by Stoesser et al. While the resolution of the LBM computation is still coarser, convergence can be clearly by inferred.

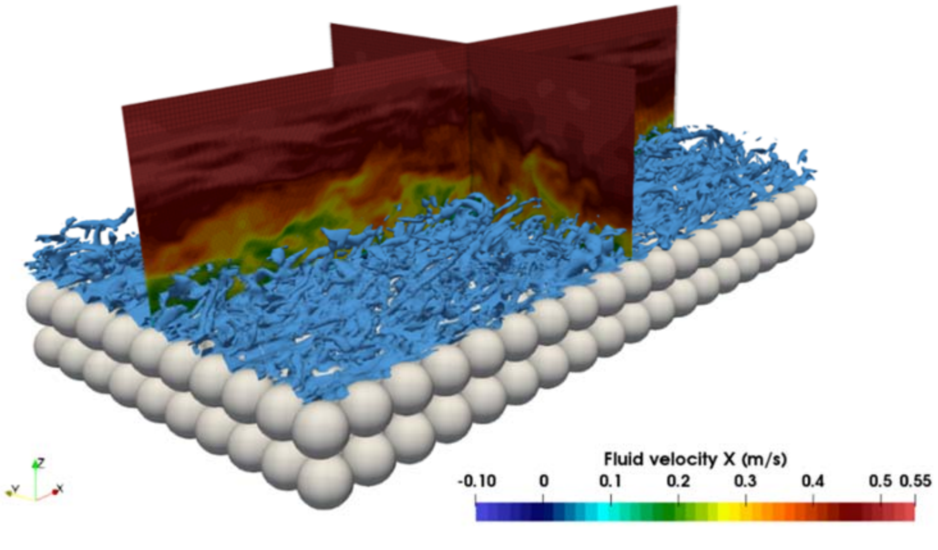

Figure 1: LES of turbulent boundary layer flow over surface consisting of two regular layers of spheres with the adaptive LBM. Colour plot of tangential velocity field with cell resolution.

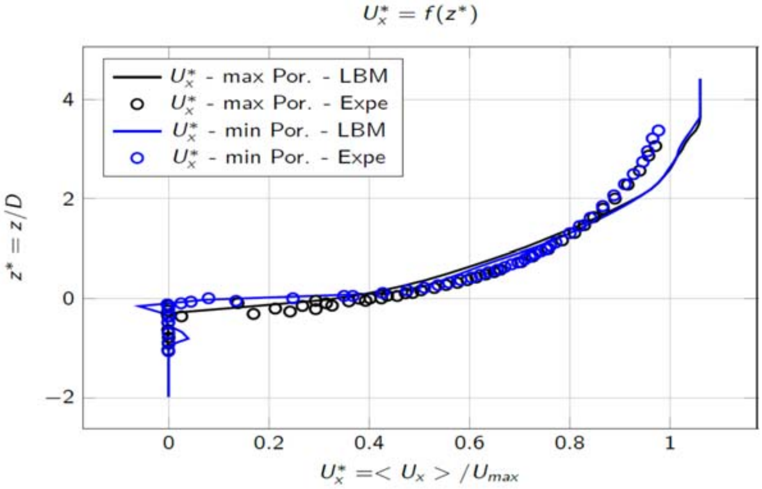

Figure 2: Averaged velocity in tangential direction in the present (LBM) computation vs. reference result (Expe).

A strong scalability benchmark on the UK Archer system of AMROC-LBM has been also been carried out for the prototype setup. Starting from a 360x240x108 base grid and adding dynamically up to 2 additional levels refined in all spatial directions by factors 2 and 4, respectively, the benchmark computation corresponds to a uniform mesh of 2880x1920x864 = 4.78e9 cells. The benchmark computed 80 timesteps on the finest grid level and included 4 complete parallel mesh redistributions. 24,844,504 cells where used at the end of this test on the first refinement level and 10,838,016 on the second. Figure 3 displays the speedup of the parallel computation with increasing core count compared to the ideal line. Since the LBM is computational rather inexpensive, parallel scalability on very large processor number is difficult to achieve when mesh adaptation is employed. At least until 1536 cores the performance gains from using more processors are quite acceptable for our implementation.

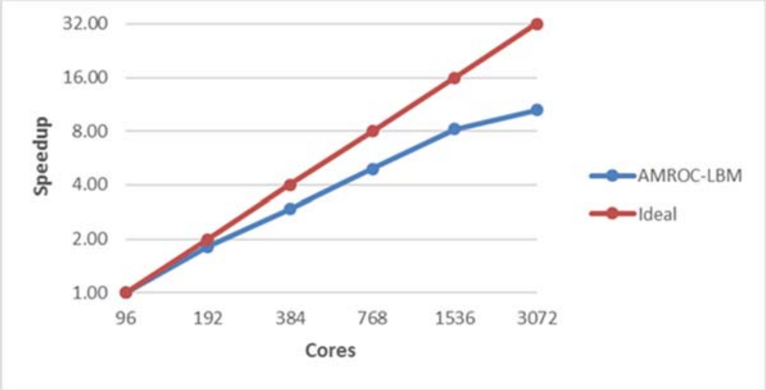

Figure 3: AMROC-LBM speedup versus core number.

4 Conclusions and Contributions

LES of turbulent boundary layer flow over a generic prototype rough and permeable surface have been carried out with our self-developed parallel and dynamically adaptive lattice Boltzmann code AMROC-LBM. Good agreement with available reference data is achieved already and verifies the correctness of the adaptive LBM and LES implementation.

While scalability of the explicit AMROC-LBM code when running in static, uniform grid mode is up to O(10,000) cores (not included here), benchmark computations have confirmed good scalability of AMROC-LBM on hierarchical, self-adapting meshes on O(1000) cores for a prototype surface. At the conference significantly higher resolved simulations of LES over technically relevant surface geometries will be presented. The preliminary studies discussed here have confirmed the suitability of our overall approach.

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References

[1] M.M. Fragner, R. Deiterding, “Investigating cross-wind stability of high-speed trains with large-scale parallel CFD”, International Journal of Computational Fluid Dynamics, 30(6), 402-407, 2016.

[2] R. Deiterding, “Block-structured adaptive mesh refinement - theory, implementation and application”, European Series in Applied and Industrial Mathematics: Proceedings, 34, 97-150, 2011.

[3] R. Deiterding and S. L. Wood, “An adaptive lattice Boltzmann method for predicting wake fields behind wind turbines”, in A. Dillmann et al. (Editors), “New Results in Numerical and Experimental Fluid Mechanics X” (Notes on Numerical Fluid Mechanics and Multidisciplinary Design; No. 132), Cham, CH: Springer, 2016.

[4] K. Feldhusen, R. Deiterding, C. Wagner, “A dynamically adaptive lattice Boltzmann method for thermal convection problems”, International Journal of Applied Mathematics and Computer Science, 26(4), 735-747, 2016.

[5] R. Deiterding, S. L. Wood, “Predictive wind turbine simulation with an adaptive lattice Boltzmann method for moving boundaries”, Journal of Physics: Conference Series, 753, 82005, 2016.

[6] C. Laloglu, R. Deiterding, “Simulation of the flow around an oscillating cylinder with adaptive lattice Boltzmann methods”. In P. Ivanyi, B. H. V. Topping, G. Varady (Editors), “Proceedings of the Fifth International Conference on Parallel, Distributed, Grid and Cloud Computing for Engineering”, 2017.

[7] T. Stoesser, J. Fröhlich, W. Rodi, “Large eddy simulation of open-channel flow over and through two layers of spheres”, in “7th Int. Conf. on Hydroscience and Engineering” (ICHE-2006), 2006.

[8] D. Hähnel, “Molekulare Gasdynamik“, Springer, 2004.

[9] S. Hou, J. Sterling, S. Chen, G. D. Doolen, “A lattice Boltzmann subgrid model for high Reynolds number flows”, in: A. T. Lawniczak, R. Kapral (Editors), “Pattern formation and lattice gas automata”, Fields Inst Comm, 151-166, 1996.