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EXTENDED COMPARISON BETWEEN LATTICE BOLTZMANN AND NAVIER-STOKES SOLVERS FOR UNSTEADY AERODYNAMIC AND AEROACOUSTIC COMPUTATIONS

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INTRODUCTION

Within the past decades, Computational Fluid Dynamics (CFD) has dramatically risen in the aerospace industry enabling the simulation of configurations of growing complexity. The increasing computational power and the growing need of high-fidelity methods owing to new sustainable aviation objectives have lead to the development of Large Eddy Simulations (LES). As indicated by Löhner [1], structured finite-type Navier-Stokes (NS) methods and lattice Boltzmann methods (LBM) may be the first to achieve industrial-level LES.

While LES or hybrid RANS-LES applied to the Navier-Stokes equations are well established and studied approaches, the LBM, which relies on a mesoscopic description of collisions between fluid particles, has gradually emerged as an interesting alternative for the LES of weakly compressible flows [2]. Consequently, one question which naturally arises is: Which method is the most competitive, in terms of accuracy and computational cost, on canonical aerodynamic and aeroacoustic applications ?

Previous work on the comparison between the LBM and traditional NS methods focused on different topics such as convergence order [3], achievable error [4], and runtimes [5]. However, there still is a lack of fair one-to-one comparisons. Indeed, most runtime-based results were obtained with two different solver developed independently and having different levels of optimisation. In addition, the numerical properties of the lattice Boltzmann method are highly dependent on the selected collision operator [6, 7] such that the conclusions of [4], only considering the BGK model, have to be tempered.

SCOPE OF THIS CONTRIBUTION

This work aims at rigorously comparing a lattice Boltzmann solver with an LES-type finite-volume Navier-Stokes solver. The comparison is performed using ONERA's Cassiopée/Fast CFD environment implementing high-performance flow solvers which rely on the same code architecture and optimisation layers (see Figure 1).

MEANS AND METHOD OF COMPARISON

Firstly, the lattice Boltzmann method is compared to traditional finite-type Navier-Stokes schemes through von Neu-

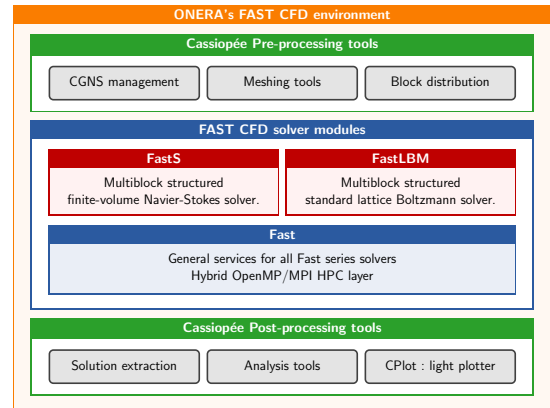


Figure 1: ONERA's Cassiopée/Fast CFD environment used for the comparison between the lattice Boltzmann and Navier-Stokes methods.

mann analyses. The latter consist in a linearisation of the corresponding algorithm about a mean flow and allow to investigate the behavior of linear waves in terms of propagation and dissipation. To do so, the von Neumann analysis introduced in [4] is extended by taking into account regularised LB collision models representative of those used for industrial-levels computations. Moreover, recent advances in LB linear stability analyses [6] set the path towards two-dimensionnal wavenumber plane studies. By applying this idea to NS schemes, isotropy defects are highlighted for both numerical methods as shown on Figure 2. These defects are attributed to the coupling between spatial and temporal discretisations.

The results obtained by means of the von Neumann analyses are then validated through numerical test cases. The computation of monochromatic acoustic and shear plane waves gives an estimate of the number of points per wavelength required by each method to reach a certain error target. In addition, test cases representative of canonical aerodynamic problems such as a vortex convection (see Figure 3 for a qualitative comparison) and a 3D Taylor Green Vortex are considered. The influence of the LB collision model and NS spatial and time-stepping schemes are thoroughly discussed throughout the entire validation process.

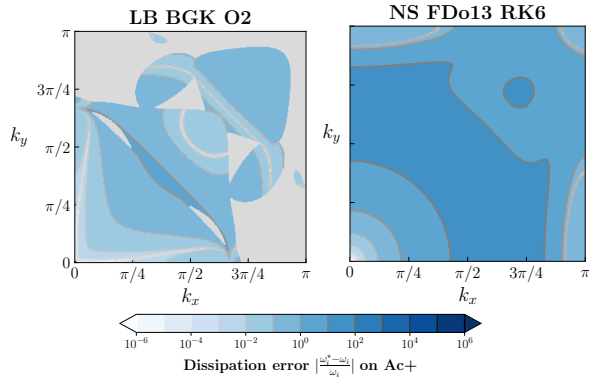


Figure 2: Dissipation error on the acoustic mode computed through the von Neumann analysis in a fluid medium at rest. Left : lattice Boltzmann BGK. Right: Navier-Stokes with 6th-order centered optimised spatial scheme.

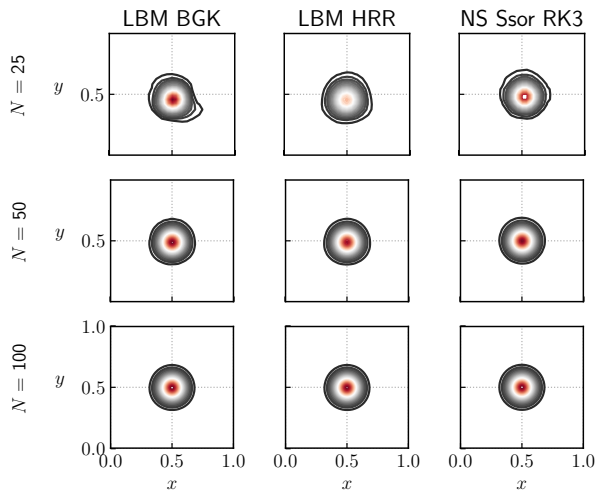


Figure 3: Comparison of the vortex shape obtained by two LBM and one NS computations after 5 advection cycles for three different resolutions where N is the number of mesh points per unit length.

Finally, the CPU performance of both solvers is studied. The Roofline model [8], reformulated in “cell update” units, is applied to the lattice Boltzmann and finite-volume Navier-Stokes algorithms. Estimates about the maximum attainable performance are obtained and the main bottlenecks of the core loop of both solvers are evidenced.

Single-node scaling is performed and the measured performances are confronted to the Roofline model estimates. A “time to solution” metric is also introduced in order to fairly compare the LB and NS methods. It is shown that, in contrast to LB solvers, the “time to solution” of NS schemes does not only depend on the number of points per wavelength but also on the CFL number.

The results of this extended comparison exhibit that a fluid cell update is about two to three times faster with the lattice Boltzmann method w.r.t the finite-volume Navier-Stokes solver (see Figure 4). Regardless of the collision operator, the LB solver is especially suited for acoustic applications, offering speedups up to 10 compared to an LES-type NS solver.

On more “realistic” test cases such as a vortex convection or a 3D Taylor Green vortex, it is demonstrated that good qualitative results can be obtained in competitive runtimes with lattice Boltzmann methods. The latter perform outstandingly well for very low resolutions. However, for highly accurate results measured through L^2 or L^∞ norms, the finite-volume Navier-Stokes method outperforms the lattice Boltzmann solver in terms of “time to solution”.

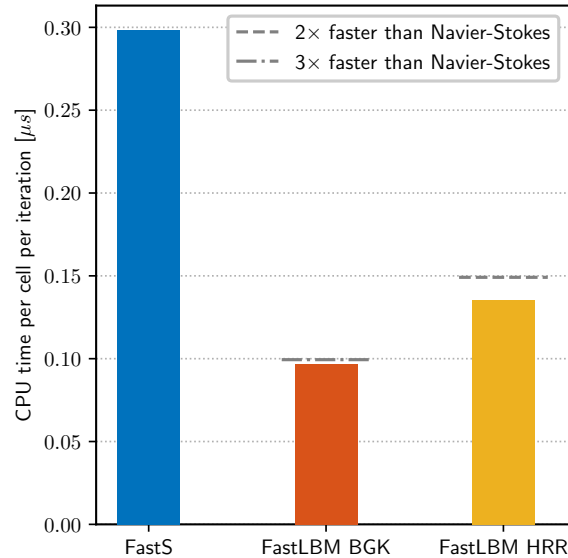


Figure 4: CPU time per cell per iteration for the FV-NS solver on structured cartesian grids and for the LBM with BGK and HRR [7] collision operators.

REFERENCES

- [1]Löhner R. : Towards overcoming the LES crisis, *International Journal of Computational Fluid Dynamics*, **33**, 87–97 (2019).
- [2]Touil H., Ricot D., and Lévêque E. : Direct and large-eddy simulation of turbulent flows on composite multi-resolution grids by the lattice Boltzmann method, *Journal of Computational Physics*, **256**, 220–233, (2014).
- [3]Noble D. R., Georgiadis J. G., and Buckius R. O. : Comparison of accuracy and performance for lattice Boltzmann and finite difference simulations of steady viscous flows, *International Journal for Numerical Methods in Fluids*, **23**, 1–18 (1996).
- [4]Marié S., Ricot D., and Sagaut P. : Comparison between lattice Boltzmann method and Navier-Stokes high order schemes for computational aeroacoustics, *Journal of Computational Physics*, **228**, 1056–1070 (2009).
- [5]Wichmann K.-R., Kronbichler M., Löhner R., and Wall W. A. : A runtime based comparison of highly tuned lattice Boltzmann and finite difference solvers, *International Journal of High Performance Computing Applications*, 370–390, (2021).
- [6]Wissocq G., Coreixas C., and Bousuge J.-F. : Linear stability and isotropy properties of athermal regularized lattice Boltzmann methods, *Physical Review E*, **102**, (2020).
- [7]Jacob J., Malaspinas O., and Sagaut P., “A new hybrid recursive regularised Bhatnagar–Gross–Krook collision model for lattice Boltzmann method-based large eddy simulation,” *J. Turbul.*, **19**, 1051–1076, (2019).
- [8]Williams S., Waterman A., and Patterson D. : Roofline: an insightful visual performance model for multicore architectures, *Commun. ACM*, **52**, 65–76, (2009).