PROPOSITION DE SUJET DE THESE

Intitulé : Probing of lattice Boltzmann methods for compressible flows

Référence : **SNA-DAAA-2025-08**
(à rappeler dans toute correspondance)

Début de la thèse : 1/10/2025	**Date limite de candidature : 15/6/2025**

Mots clés

Numerical simulation, lattice Boltzmann method, numerical methods, high-performance computing, numerical analysis.

Profil et compétences recherchées

Master or engineering school + master. Solid background in fluid mechanics (compressible flow theory, turbulence modeling, etc.) and applied mathematics (numerical methods, numerical analysis). Good programming skills (Python, C/C++, Fortran). Knowledge of the lattice Boltzmann method is appreciated.

Présentation du projet doctoral, contexte et objectif

The numerical simulation of compressible flows is critical in various industrial sectors, particularly aerospace. Understanding high-speed compressible flows is, in fact, essential to the design of aircraft, rockets and atmospheric re-entry vehicles. Furthermore, simulating flows within aerospace engines demands precise modeling of the complex phenomena associated with fluid compressibility. Therefore, continuously enhancing flow simulation capabilities is vital for manufacturers to meet stringent safety requirements while addressing the challenges of reducing emissions and noise, thereby contributing to the goals of more sustainable aviation.

Traditionally, the simulation of compressible flows has relied on so-called “Navier-Stokes” methods, where the equations of fluid dynamics are solved using classical numerical techniques such as finite volume or finite difference methods [1]. Although these approaches remain widely used, they often struggle to satisfy the growing industrial requirements for accuracy and computational efficiency. This limitation becomes especially pronounced when modelling intricate phenomena such as unsteady turbulent flows and aeroacoustic effects.

In this context, the Lattice Boltzmann Method (LBM) [2] has recently emerged as a promising alternative for numerical simulation in Computational Fluid Dynamics (CFD). Unlike traditional approaches based on the Navier-Stokes equations, the LBM employs a mesoscopic description of fluids by tracking the evolution of a particle distribution function governed by the Boltzmann equation. This mesoscopic perspective offers notable advantages, such as low numerical dissipation and a high-performance evolution algorithm [3]. Additionally, it simplifies the handling of complex geometries through the combined use of automatically generated Cartesian meshes and immersed boundary conditions. These features make the LBM a particularly competitive method for a wide range of applications, both in academia and industry, as illustrated in Figure 1.

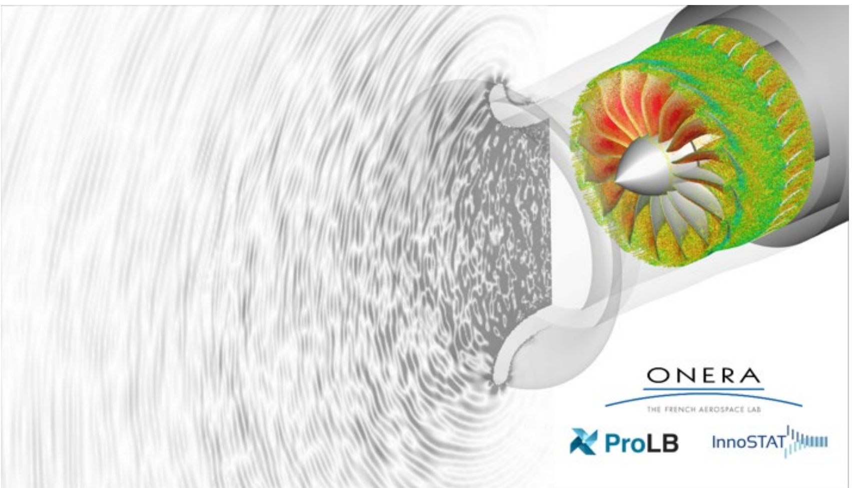

Figure 1 - Example of high-fidelity simulation using the lattice Boltzmann method.

However, in its “standard” formulation, the lattice Boltzmann method is restricted to the simulation of isothermal and weakly compressible flows, typically with Mach numbers below 0.3. Extending the LBM to the simulation of compressible flows remains a significant challenge. Overcoming scientific barriers related to the method’s stability, accuracy, and its ability to handle high Mach regimes is essential for it to become a competitive alternative to traditional CFD methods at an industrial scale.

However, this limitation is on the verge of being overcome thanks to recent advances in the field. In recent years, numerous research efforts have led to the development of promising variants of the lattice Boltzmann method for simulating compressible flows [4]. One significant advancement suggested by many researchers is to decouple the conservation equations for mass and momentum from the conservation of energy. This can be achieved through a “hybrid” formulation, where the LBM is used to solve the conservation equations of mass and momentum, while finite volume or classical finite difference schemes are employed for the conservation equation of energy [5,6]. Another approach involves decoupling the dynamics of the energy equation from the other equations by introducing a second distribution function and, consequently, a second lattice Boltzmann scheme [7,8]. While other methodologies exist, these two appear to be the most promising for industrial-scale applications, as evidenced by their integration into commercial LBM software such as SIMULIA PowerFLOW and ProLB, and by the example simulations presented in Figure 2.

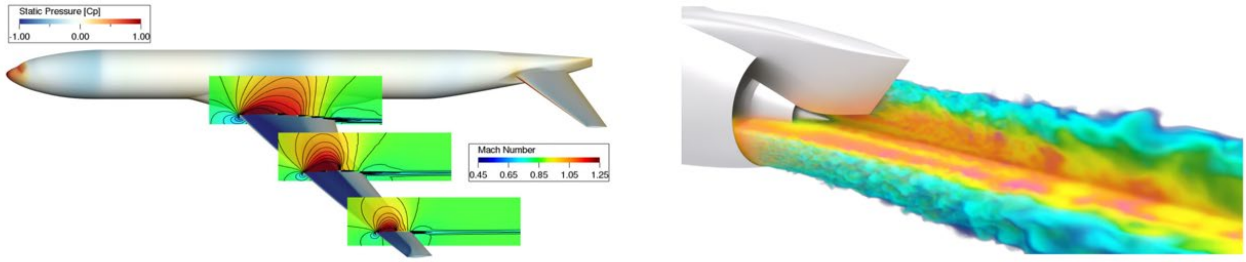

Figure 2 - Example of simulations using a compressible Boltzmann lattice method.
Left: calculation performed with SIMULIA PowerFlow [9]. Right: calculation with ProLB [10].

Despite these advances, several fundamental questions remain unanswered. The comparison between the two approaches mentioned above - the hybrid method and the use of two distribution functions - has not been fully explored. What are the respective advantages and limitations of each strategy in terms of accuracy, numerical stability and computational cost? The choice of the energy equation to be discretized is also a topic of debate: should the total energy, internal energy, or entropy equation be preferred, and how do these choices impact the results? In addition, the implementation of efficient shock sensors to manage discontinuities in compressible flows remains an open and under-researched issue within the context of the LBM. It is also crucial to evaluate the competitiveness of the compressible LBM compared with conventional Navier-Stokes methods: under what conditions can the LBM offer a genuine advantage? Resolving these questions is essential to enhance the reliability and efficiency of LBM-based simulations for compressible flows and, consequently, to meet the demands of industrial applications.

In this context, this thesis aims to conduct an in-depth study and analysis of various lattice Boltzmann method adapted variants adapted to the simulation of compressible flows. The objective is to identify the theoretical and numerical obstacles that limit its application in high-compressibility regimes, while exploring ways to enhance its robustness and accuracy. Ultimately, the ambition is to contribute to the development of more efficient lattice Boltzmann methods, capable of meeting the increasing demand for high-fidelity simulations, particularly in the aeronautics and aerospace sectors.

All the proposed research will be conducted within ONERA’s Cassiopée/Fast environment, which includes a pre-, co-, and post-processing tools for CFD and an in-house lattice Boltzmann solver optimized for high-performance computing. The PhD student may also be asked to develop and perform calculations using the industrial code ProLB, utilized by Airbus and Safran and developed in collaboration with ONERA

Bibliography:

[1] Pirozzoli, S. (2011). Numerical Methods for High-Speed Flows. Annual Review of Fluid Mechanics, 43, 163–194.

[2] Krüger, T., Kusumaatmaja, H., Kuzmin, A., Shardt, O., Silva, G., & Viggen, E. M. (2017). The Lattice Boltzmann Method: Principles and Practice. Springer International Publishing.

[3] Suss, A., Mary, I., Le Garrec, T., & Marié, S. (2023). Comprehensive comparison between the lattice Boltzmann and Navier–Stokes methods for aerodynamic and aeroacoustic applications. Computers & Fluids, 257, 105881.

[4] Hosseini, S. A., Boivin, P., Thevenin, D., & Karlin, I. (2024). Lattice Boltzmann methods for combustion applications. Progress in Energy and Combustion Science, 102, 101140.

[5] Farag, G., Coratger, T., Wissocq, G., Boivin, P., & Sagaut, P. (2021). A unified hybrid lattice-Boltzmann method for compressible flows: Bridging between pressure-based and density-based methods. Physics of Fluids, 33(8), 086101.

[6] Guo, S., & Feng, Y. (2024). Hybrid compressible lattice Boltzmann method for supersonic flows with strong discontinuities. *Physics of Fluids*, *36*(7).

[7] Li, Q., He, Y. L., Wang, Y., & Tao, W. Q. (2007). Coupled double-distribution-function lattice Boltzmann method for the compressible Navier-Stokes equations. *Physical Review E*, *76*(5), 056705.

[8] Saadat, M. H., Bösch, F., & Karlin, I. (2019). Lattice Boltzmann model for compressible flows on standard lattices: Variable Prandtl number and adiabatic exponent. *Physical Review E*, *99*(1), 013306.

[9] König, B., & Fares, E. (2016). Validation of a transonic lattice-boltzmann method on the NASA common research model. *54th AIAA Aerospace Sciences Meeting*.

[10] Daviller, G., Charles, E., Boussuge, J. F., Renard, F., & Huber, J. (2024). Investigation of Jet-Pylon Interaction Noise Using LBM. 30th AIAA/CEAS Aeroacoustics Conference.

Collaborations envisagées

Laboratoire DynFluid (CNAM / ENSAM)

Laboratoire d'accueil à l'ONERA
Département : Aérodynamique, Aéroélasticité, Acoustique
Lieu (centre ONERA) : Châtillon
Contact : Alexandre Suss
Tél. : +33 1 46 73 48 46 Email : alexandre.suss@onera.fr

Directeur de thèse
Nom : Simon Marié
Laboratoire : DynFluid (CNAM / ENSAM)
Tél. : +33 1 44 24 64 31
Email : simon.marie@cnam.fr

Pour plus d'informations : https://www.onera.fr/rejoindre-onera/la-formation-par-la-recherche