ONERA

THE FRENCH AEROSPACE LAB

www.onera.fr

PROPOSITION DE SUJET DE THESE

Intitulé : High-order adaptive numerical simulation of the sonic boom propagation

Référence : **SNA-DAAA-2021-18**
(à rappeler dans toute correspondance)

Début de la thèse : Octobre 2022	**Date limite de candidature :** Avril 2022

Mots clés

Sonic boom, nonlinear acoustics, discontinuous Galerkin method, discretization adaptation

Profil et compétences recherchées

A solid background in Computational Mechanics (numerical analysis of PDEs), programming skills and motivation to learn are required.

Formation: M.Sc. degree in Applied Mathematics, Mechanics or a related discipline, with excellent academic records.

Présentation du projet doctoral, contexte et objectif

The Concorde supersonic passenger airliner which had its speed limited during flight over residential areas [1]

In this work, we consider the full-field simulation of the **sonic boom propagation** using an accurate and adaptive numerical method. The sonic boom consists in a strong acoustic disturbance resulting from shock waves generated by aircrafts in supersonic flight. The shock waves coalesce into a single wave with a characteristic N shape that propagates in the farfield along very long distances. The associated pressure variations cause strong noise pollution on the ground and prevent the supersonic flight over land. The analysis of this phenomenon is therefore of strong interest for the design of "low-boom" aircraft shapes that would reduce the loudness of the boom at the ground to make supersonic flight over land possible and hence reduce travel time.

The numerical simulation of the sonic boom phenomenon is however challenging due to its multiscale and multiphysics nature. The acoustic waves must be accurately propagated over very long distances (several kilometers) compared to the size of the aircraft and the simulation must resolve very small time and space scales up to the ground. The most commonly employed approach consists in coupling a CFD solver, to evaluate the flow around the aircraft, with an acoustic solver based on geometrical acoustic theory [2]. This approach however presents several limitations which derive from the high frequency approximation and the lack of the inclusion of diffraction effects. Due to these limitations, geometrical acoustic theory leads to the prediction of infinite amplitude acoustic perturbations in the presence of sonic boom focusing, e.g. during maneuvering or acceleration of the aircraft or high Mach speed flight [3]. Additionally, no signal is predicted in the shadow zone, an area surrounding the flight path where no boom is heard due to the refraction caused by atmospheric stratification.

The main objective of this research project is the development of a CFD solver for the simulation of sonic boom propagation including the influence of various physical phenomena. These include viscosity, molecular relaxation, thermochemical non-equilibrium and various atmospheric conditions to provide accurate and reliable predictions of the wave structure. In this context we propose to use and analyze a high-order **discontinuous Galerkin method** (DGM) for the discretization of the **nonlinear compressible multi-component Navier-Stokes equations**. The DGM is a compact finite element method which looks for a piecewise polynomial approximate solution. The method results in very low dispersion and dissipation errors which are essential features for wave problems. Additionally, it is a flexible method in the sense that it allows to adapt locally the approximation order and the cell size on unstructured meshes. Both aspects will constitute key ingredients for the efficiency of the simulations.

Two main issues will be addressed during this work. First, the DGM suffers from spurious oscillations (associated to the Gibbs phenomenon) around discontinuities such as shock waves. Classical shock-capturing techniques successfully damp oscillations around strong shocks but may affect the resolution of nonlinear waves of small amplitude as in the sonic boom. Care will be taken to the design of a robust and accurate DGM based on the concepts of skew-symmetric decomposition of the convective fluxes [4] and artificial viscosity [5]. In particular, we will investigate the conditions on the numerical parameters to obtain a nonlinearly stable, positive and well-balanced (preservation of some steady state solutions) scheme.

Then, the large size of the computational domain compared to the scale of resolution leads to important computational requirements. Local **adaptation** of the numerical scheme in terms of approximation order and cell size will be applied to reduce the CPU cost of the simulation. The method is based on local error estimates that automatically adapt the scheme accuracy to the local physical scales [6] and thus reduce the size of the discrete problem without compromising its accuracy. We will also investigate optimal hp adaptation strategies for this specific phenomenon.

Numerical experiments in the code Aghora developed at ONERA will be conducted to assess the performances of the method. The method will then be used to investigate the cut-off phenomena at low supersonic speeds and the effects of a real atmosphere (viscosity, relaxation, stratification) on the wave structure. The results obtained during this PhD work will be the subject of publications in academic journals and scientific conferences.

Bibliography:

[1] https://commons.wikimedia.org/w/index.php?curid=20897820

[2] G. B. Whitham. "On the propagation of weak shock waves". Journal of Fluid Mechanics 1.03 (1956), pp. 290–318.

[3] J.-C. L. Wanner, J. Vallee, C. Vivier, and C. Thery. "Theoretical and Experimental Studies of the Focus of Sonic Booms". The Journal of the Acoustical Society of America 52.13 (1972), pp. 13–32.

[4] M. H. Carpenter, T. C. Fisher, E. J. Nielsen and S. H. Frankel. Entropy stable spectral collocation schemes for the Navier–Stokes equations: discontinuous interfaces. SIAM J. Sci. Comput., 36 (2014), B835-B867.

[5] J.-L. Guermond, R. Pasquetti, B. Popov, Entropy viscosity method for nonlinear conservation laws, J. Comput. Phys., 230 (2011), 4248-4267.

[6] F. Naddei, M. de la Llave Plata, V. Couaillier and F. Coquel, A comparison of refinement indicators for p-adaptive simulations of steady and unsteady flows using discontinuous Galerkin methods, J. Comput. Phys., 376 (2019), 508-533

Collaborations envisagées

CMAP, École Polytechnique, 91128 Palaiseau Cedex / Sorbonne Université, 75006 Paris / Inria, Université Paris-Saclay, 91120 Palaiseau

Laboratoire d'accueil à l'ONERA	**Directeur de thèse**
Département : Aérodynamique, Aéroélasticité, Acoustique	Nom :
Lieu (centre ONERA) : Châtillon	Laboratoire :
Contact : Fabio Naddei	Tél. :
Tél. : +33 1 46 73 42 02	Email:
Email : fabio.naddei@onera.fr	

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