www.onera.fr

PROPOSITION DE SUJET DE THESE

Intitulé : Scale-resolving simulations of wall-bounded turbulent flows at high Mach and Reynolds numbers

Référence : **MFE-DAAA-2024-30**
(à rappeler dans toute correspondance)

Début de la thèse : Octobre 2024	**Date limite de candidature :** 01/07/2024

Mots clés

Modélisation de la turbulence, méthodes hybrides RANS/LES, ZDES, supersonique, hypersonique

Profil et compétences recherchées

Formation : Master 2 ou ingénieur + master 2

Spécificités souhaitées : Formation solide en mécanique des fluides (théorie, en particulier turbulence, et méthodes numériques). Goût pour l'analyse physique et pour la programmation. Notions en Intelligence Artificielle appréciées.

Présentation du projet doctoral, contexte et objectif

High-Mach number flows encountered around supersonic or hypersonic vehicles feature very complex turbulent phenomena, such as viscous interactions involving wall-bounded turbulence. As an example, the efficiency and operational reliability of a supersonic inlet relies on the proper prediction of the shock wave - boundary layer interactions, as illustrated in Figure 1. However, such phenomena are difficult to capture with Reynolds-averaged (RANS) approaches because turbulence models are usually derived in an incompressible framework while strong compressibility effects should be taken into account, and the models derivation often relies on equilibrium assumptions. Moreover, the broadband spectral content in the unsteady separated regions of the flow cannot be resolved by RANS approaches. This motivates so-called scale-resolving simulations where turbulent fluctuations are resolved rather than modelled, explicitly resolving the effects of compressible and out-of-equilibrium turbulence and strong unsteadiness which cause difficulties to derive truly universal RANS models.

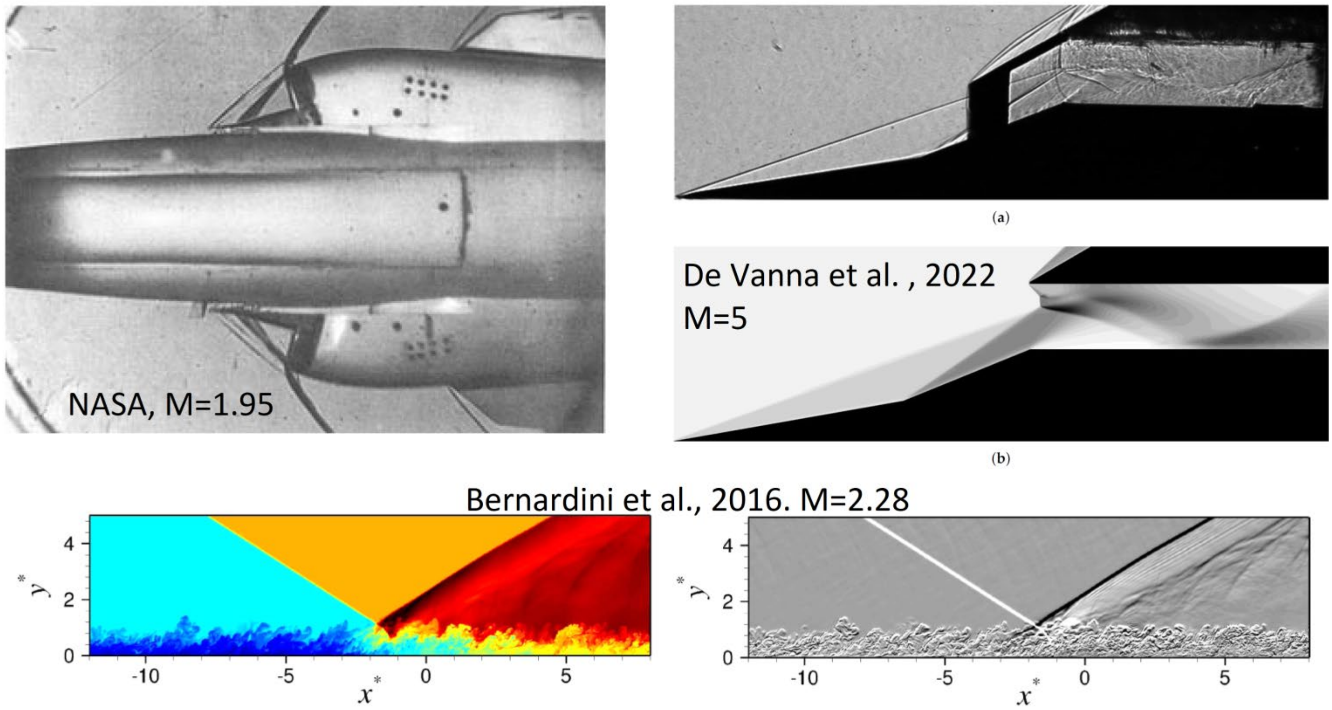

Figure 1 : Supersonic and hypersonic inlets, shock wave / boundary layer interactions

A major issue with scale-resolving approaches is the computational cost of resolving turbulence, which increases very quickly with the Reynolds number, leading to the impossibility to perform a Direct Numerical Simulation (DNS) of all turbulent scales around a real-life geometry at its design Reynolds number. Even the LES approach aiming to resolve only the largest turbulent scales while modelling the smallest ones fails to procure affordable computational costs when resolving near-wall turbulence at applicative Reynolds numbers. This has motivated the development of hybrid RANS/LES methods which enable to focus only on the regions of the flow where the LES approach is needed while the rest of the flow is treated in RANS at a relatively low computational cost. ONERA has been developing one such method since 2002, named Zonal Detached Eddy Simulation (ZDES) [1], thanks to which the regions of interest of the turbulent flow (*e.g.* the turbulent jets in Figure 2) may be studied in detail by a LES resolution whereas the rest of the flow is represented on average (RANS), leading to a cost reduction factor larger than 50 in typical applications compared with DNS. This means it becomes computationally affordable to keep the real Reynolds number of the application, as illustrated by Figure 2. The ZDES approach is now both established in the academic world [3,4] and used by the major companies of the French aeronautic sector as a high-fidelity computational tool for industrial risk mitigation [2]. The method has been recently improved [5] for a better automatic detection of the zones that should be treated in RANS or in LES.

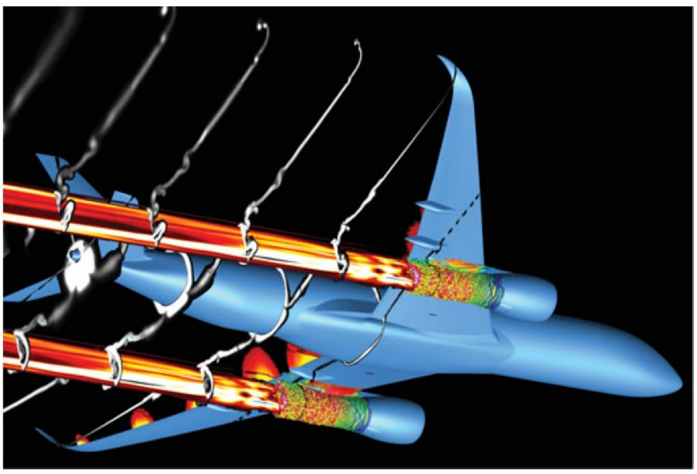

Figure 2 : Example of application of the ZDES technique to a real-life geometry: full airliner in cruise conditions [2]

The doctoral work will focus on high Mach number flows (typically between 2 and 5), where specific questions arise:

- How can resolved turbulence be generated in the LES regions that are fed by averaged RANS descriptions, as efficiently and quietly (in a spurious acoustics sense) as possible in spite of the strong compressibility of the flow?
- What degree of resolution is needed to capture phenomena such as a shock wave / boundary layer interaction? Should only the separated regions be treated in LES or also the outer layer of the incident attached boundary layers?
- When the outer layer is LES-resolved and the inner layer is treated by RANS, what are the effects of the Mach number on the RANS/LES interface behaviour? What is the degree of resolution of turbulent heat fluxes?

Such questions may be addressed in academic test cases such as a zero-pressure-gradient flat plate turbulent boundary layer with adiabatic or cooled wall, or a shock-wave / boundary layer interaction including complex features such as Görtler-like vortices. The main expected outputs are a more efficient and silent technique to generate resolved turbulence and a better understanding of the near-wall RANS / outer LES interface at high Mach numbers. The analysis of the weight of the underlying RANS model and of the resolved turbulence in the prediction of the turbulent heat flux may rely on a parallel with the physical decomposition of mean skin friction developed in the past for the investigation of ZDES [6]. The results may lead to suggestions for improvements of the RANS model itself. Beyond classical turbulence modelling techniques, the candidate will be encouraged to explore new options such as the possibilities offered by Artificial Intelligence.

The proposed evolutions of the hybrid RANS/LES approaches will finally be applied to industrial configurations such as a supersonic inlet or a hypersonic cone-cylinder-flare geometry in order to demonstrate the methodological improvement of ZDES. The latter application is related to the federating research project PRF FREHYA led by ONERA together with CEA. This project aims to better understand and model transition and turbulence in cold hypersonic flows through experimental and numerical approaches considering a common cone-cylinder-flare geometry.

[1] Deck, S., Recent improvements in the Zonal Detached Eddy Simulation (ZDES) formulation, *Theoretical and Computational Fluid Dynamics*, 2012, 26, 523-550

[2] Deck, S.; Gand, F.; Brunet, V. & Khelil, S. B., High-fidelity simulations of unsteady civil aircraft aerodynamics: stakes and perspectives. Application of Zonal Detached Eddy Simulation (ZDES), *Philosophical Transactions of the Royal Society A*, 2014, 372, 20130325

[3] Deck, S.; Renard, N.; Laraufie, R. & Weiss, P.-É., Large scale contribution to mean wall shear stress in high Reynolds number flat plate boundary layers up to $Re_\theta = 13650$, *Journal of Fluid Mechanics*, 2014, 743, 202-248

[4] Vaquero, J.; Renard, N. & Deck, S., Outer layer turbulence dynamics in a high-Reynolds-number boundary layer up to $Re_\theta \approx 24000$ recovering from mild separation, *Journal of Fluid Mechanics*, 2022, 942, A42-1/32

[5] Deck, S. & Renard, N., Towards an enhanced protection of attached boundary layers in hybrid RANS/LES methods, *Journal of Computational Physics*, 2020, 400, 108970

[6] Renard, N. & Deck, S., A theoretical decomposition of mean skin friction generation into physical phenomena across the boundary layer, *Journal of Fluid Mechanics*, 2016, 790, 339-367

Collaborations envisagées

Non

Laboratoire d'accueil à l'ONERA	**Directeur de thèse**
Département : Aérodynamique, Aéroélasticité, Acoustique	Nom : Sébastien DECK
Lieu (centre ONERA) : Meudon	Laboratoire : ONERA/DAAA/MSAT
Contact : Nicolas RENARD	Tél. : 0146734347
Tél. : 0146235110 Email : nicolas.renard@onera.fr	Email : sebastien.deck@onera.fr

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