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PROPOSITION DE SUJET DE THESE

Intitulé : Scale-resolving approaches for wall-bounded turbulent flows at high Mach and Reynolds numbers

Référence : **MFE-DAAA-2026-16**
(à rappeler dans toute correspondance)

Début de la thèse : Octobre 2026 | **Date limite de candidature :** 01/10/2026

Mots clés

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

Profil et compétences recherchées

Formation : Master 2 ou ingénieur + master 2

Spécificités souhaitées : Formation solide en mécanique des fluides, appétence pour la 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

Sujet : 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 Fig 1. However, such phenomena are difficult to capture with Reynolds-averaged (RANS) approaches because the turbulence models are usually derived in an incompressible framework while strong compressibility effects should be taken into account. 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 compressibility and strong unsteadiness which cause difficulties to derive truly universal RANS models.

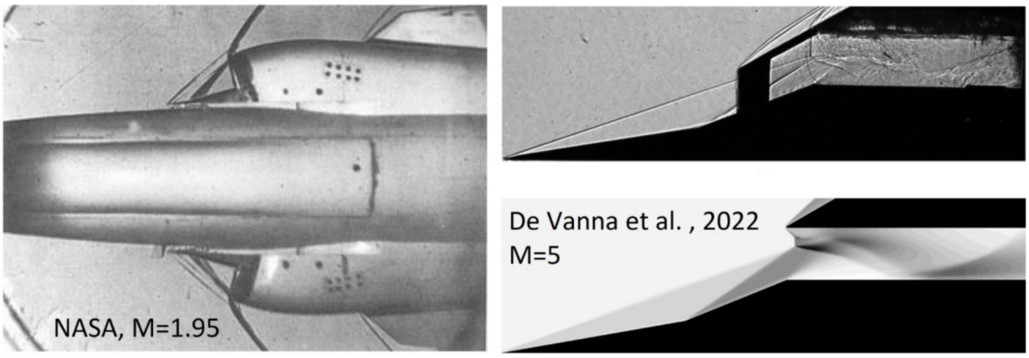

Figure 1 : Examples of flow visualisations for supersonic (left) and hypersonic (right) inlets.

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 Fig 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 in Fig 2 for an airliner in cruise conditions. The ZDES approach is now both established in the academic world [3,4] including leading CFD teams such as NASA [5] and the French aerospace and defence sector for industrial risk mitigation [2]. The method has been recently improved [6] for a better automatic detection of the zones that should be treated in RANS or in LES. Nevertheless, the best strategy to simulate turbulent boundary layers based on either RANS or WMLES approaches is still an active research field in the community and constitutes the backbone of this subject.

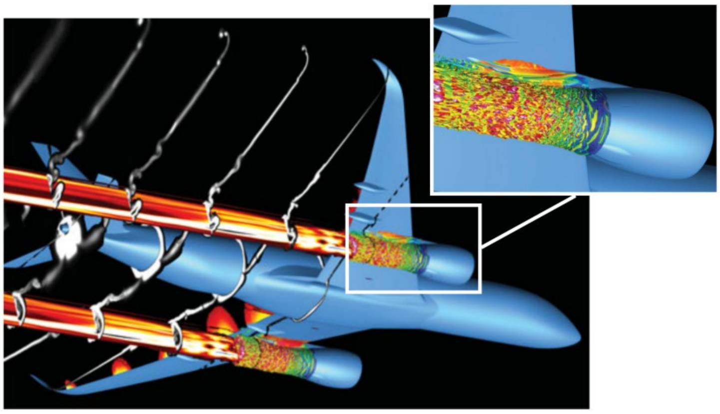

Figure 2 : Example of application of the ZDES technique to a real-life geometry: full airliner in cruise conditions [2]

Consequently, the doctoral work will focus on understanding and improving unsteady models (hybrid RANS/LES or WMLES) to simulate compressible flows for Mach numbers ranging from 2 to 5. An emphasis will be put on the study of compressible turbulent boundary layers, followed by cases involving shock wave - boundary layer interactions for which the behaviour of existing models will be assessed in detail [7]. This is a necessary step because state-of-the-art WMLES generally tend to fail at predicting the correct separation physics caused by the shock wave – boundary layer interaction as illustrated in Fig 3. Based on the results, the candidate will thoroughly investigate around key points representing current bottlenecks of turbulence modelling for such applications:

- What are the main assets and limitations of RANS and ZDES models in their current formulation for capturing the physics of shock wave – boundary layer interactions?

- How important is it to take into account turbulent fluctuations in the upstream boundary layer?

The main expected outputs are

1. a deeper understanding of the prediction ability of different types of turbulence modelling ranging from pure RANS to WMLES for shock wave - boundary layer interactions.
2. to develop and validate improvements to existing strategies on configurations of increasing complexity from canonical shock wave –boundary layer interaction towards more realistic documented applications such as supersonic intakes or missile configurations such as the configuration of Estruch-Samper and Chandola [8] presented in Fig 3.

*Although not mandatory, the thesis may be proposed to the candidate recruited for the internship entitled «***Scale-resolving simulations of wall-bounded turbulent flows at high Mach and Reynolds numbers***» dealing with a similar subject.*

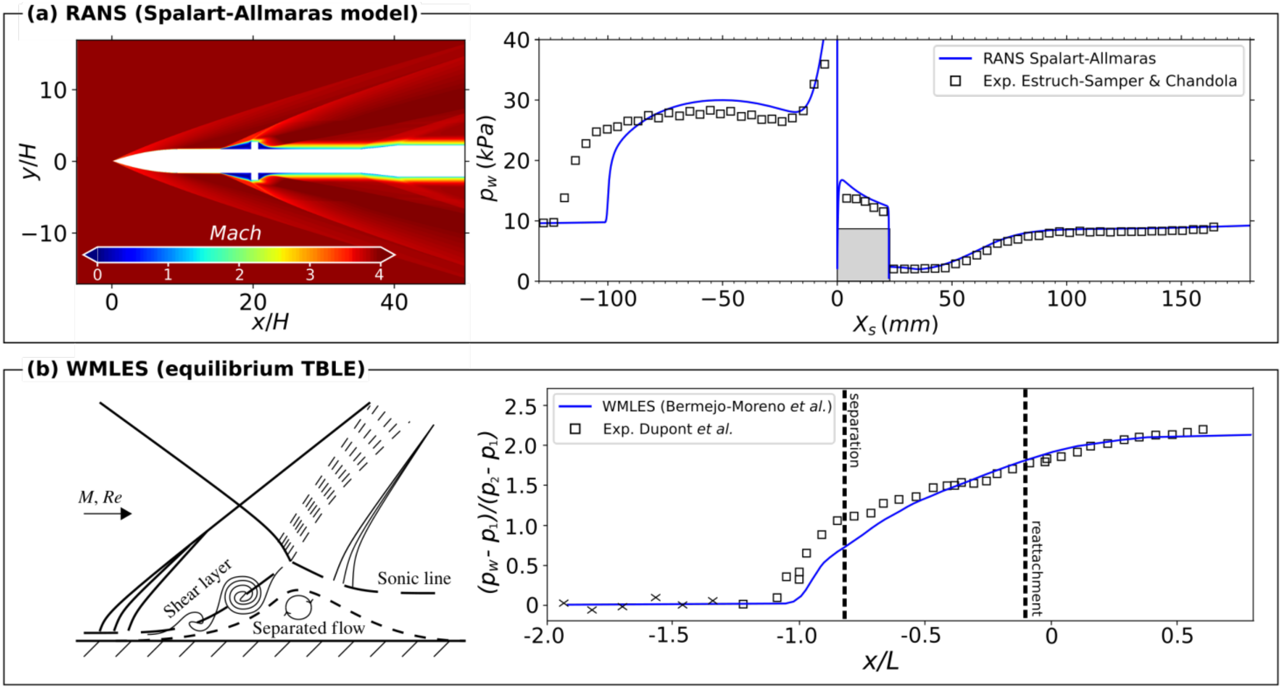

Figure 3 : Examples of mean wall pressure prediction for two very different turbulence modelling and shock wave – boundary layer interaction. (a) RANS computation of a forward facing step on an ogive-cylinder body from the experiments of Estruch-Samper and Chandola [8]. (b) equilibrium-TBLE-based WMLES simulation of an incident shock interacting with a turbulent boundary layer taken from the work of Bermejo-Moreno *et al.* [9]

Références :

[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_θ =13650, *Journal of Fluid Mechanics*, 2014, 743, 202-248

[4] Kiris, CC., et al. "High-lift common research model: RANS, HRLES, and WMLES perspectives for CLmax prediction using LAVA." AIAA SciTech 2022 Forum. 2022.

[5] 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

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

[7] Murugan, JN. et Govardhan, RN. Shock wave–boundary layer interaction in supersonic flow over a forward-facing step. Journal of Fluid Mechanics, 2016, vol. 807, p. 258-302.

[8] Estruch-Samper, D. et Chandola, G. Separated shear layer effect on shock-wave/turbulent-boundary-layer interaction unsteadiness. Journal of Fluid Mechanics, 2018, vol. 848, p. 154-192.

[9] Bermejo-Moreno, I., et al. "Confinement effects in shock wave/turbulent boundary layer interactions through wall-modelled large-eddy simulations." Journal of Fluid Mechanics 758 (2014): 5-62.

Collaborations envisagées

Non

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