Advanced Design Methodology for Laminar Boundary Layer Control

ESA Contract No. 4000139380/22/NL/GLC/rk

Executive summary report

VKI Internal Ref. VKI CR 2024-04 (ARR2105)

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ESA STUDY CONTRACT REPORT

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ABSTRACT:
The progress and key findings related to the development of a design methodology for laminar boundary layer control are summarized. Our established methodology relies on the definition of an inviscid geometry, then automatically corrected for viscous effects and ultimately followed by automated boundary layer stability predictions (Linear Stability Theory and e^N method). Our innovative methodology enables efficient parametric studies which offer a deeper insight into the fundamental physics governing boundary layer laminar-to-turbulent transition.

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0	November 28, 2023	Initial version
1	November 30, 2023	Added ESA star sheet

The laminar to turbulent boundary layer transition holds paramount importance in high-speed flow regime because of its impact on the aerodynamics performance and thermal management of the spacecraft. Accurate prediction and control of the laminar to turbulent transition are therefore imperative for optimizing hypersonic vehicle designs, ensuring efficient propulsion, aerodynamic performance, and safeguarding against the extreme aerothermal conditions encountered during hypersonic flight. Despite decades of investigations, the incomplete understanding of this phenomenon for those flow regimes still contributes to hinder the design of advanced hypersonic vehicles justifying the need for additional investigations.

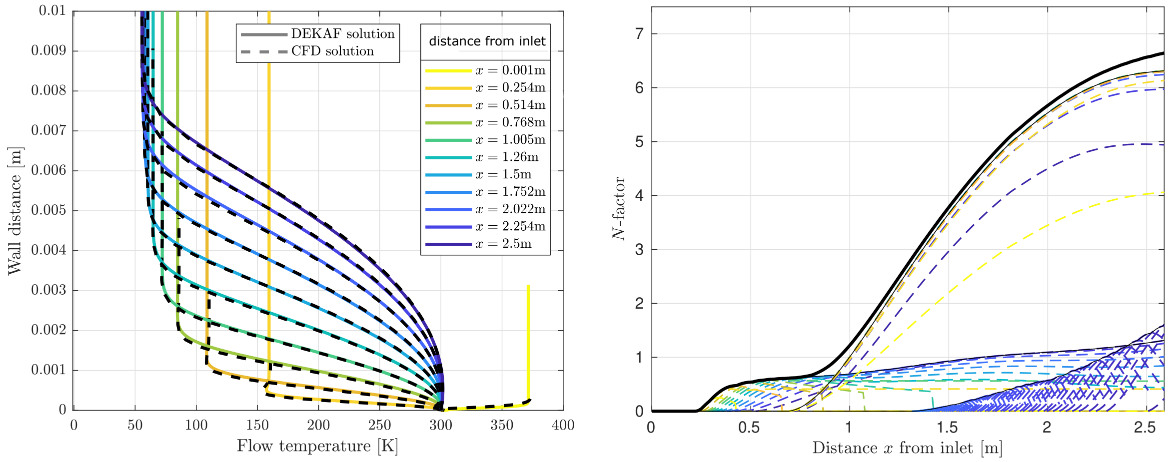
This activity focuses on the development of a methodology to design axisymmetric geometry favoring boundary layer transition delays along their profile. Three codes are chained together. First, an inviscid code provides a first geometry which is corrected to account for viscous effects using a boundary layer code. Secondly, the geometry and the boundary layer edge values are provided to the boundary layer code which predicts the displacement thickness. An iterating procedure ensures that the boundary layer code adapts to the altered curvilinear coordinate system. The advantage of this method lies in its efficient computational cost by using a boundary layer code instead of a full Computational Fluid Dynamics (CFD) solver on the entire domain. Verification of the flow quantities provided by the coupling of inviscid and boundary layer code has been performed against results of a Navier-Stokes solver. The comparison has strengthened confidence in this design process and accuracy of the approach followed (Fig. 1a). After convergence, the code provides the boundary layer profiles to a stability solver based on the Linear Stability Theory (LST). The stability code has been used to investigate the development of boundary layer instabilities computing growth rate and integrated amplitude (N-factor) along the geometry profile. The effort was focused on typical boundary layer instabilities expected in the hypersonic regime. The integrated amplitude envelope of those modes can later be compared with empirical inputs to define the transition onset location. This design approach has been proven to be efficient in terms of computational cost and robustness. Finally, very good agreement for the mode growth prediction was found with respect to literature data.

An example of the outputs of the toolset is provided in Fig. 1 showing the temperature profiles computed by the boundary layer code (compared with CFD on entire geometry) and the use of those profiles to determine the N-factor along the geometry. The growth of different instabilities can be observed as well as their mutual envelope that should be compared with the critical N-factor.

Preliminary parametric study on a baseline geometry has highlighted the design parameters that contribute the most to delay transition. In particular, the thermal boundary condition has been shown to be the most influencing parameter for the growth of instabilities. In addition, numerical sensitivity and mesh convergence studies have verified the default parameters used for the flow solvers and stability code. The first level of automation for the whole tool chain, used to perform the sensitivity analysis, has demonstrated some valuable potential for future optimization steps.

Besides, a technological barrier associated with the machining and mirror-polishing of curved flow surfaces along an axisymmetric geometry has been successfully addressed. The selection of a high-grade stainless steel material and appropriate manufacturing process has shown the capabilities to cope with strict requirements with respect to surface roughness.

Our innovative design methodology, forged through a rigorous and systematic approach, offers deep insights into the fundamental physics governing boundary layer laminar-to-turbulent transition. Such tool can be useful in many applications from hypersonic vehicle design or supersonic propulsion device. This paves the way for not just optimization but also groundbreaking advancements in this field, pushing the boundaries of what is possible.



(a) Excellent agreement between boundary layer profiles issuing from our toolchain and from reference CFD

(b) Integrated growth rate along the profile computed using LST

Figure 1: Example of results provided by the chained tool, the comparison of the temperature profile obtained using the boundary layer code with CFD is provided together with logarithm of instability integrated growth rate for three different instabilities.