Numerical investigation of the hypersonic boundary layer transition over a blunt cone using high-order discontinuous Galerkin methods

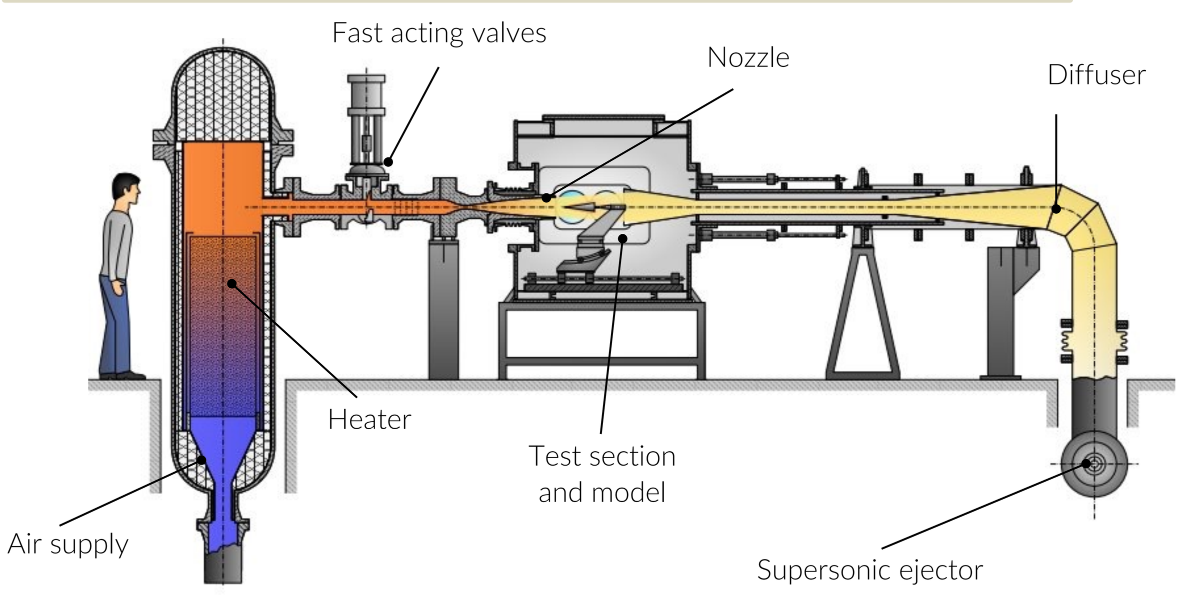
Antoine GHYOOT[1,2,3], Pierre SCHROOYEN[1], David HENNEAUX[4] , Koen HILLEWAERT[3,4], Thierry MAGIN[1,2]

[1]von Karman Institute for Fluid Dynamics, [2]Université Libre de Bruxelles, [3]Université de Liège, [4]Cenaero

Introduction

Motivations

Current efforts using Reynolds-Averaged Navier-Stokes (RANS) simulations failed to capture acoustic disturbances emanating from boundary layers in highly compressible flows.



Credits : Grossir [1]

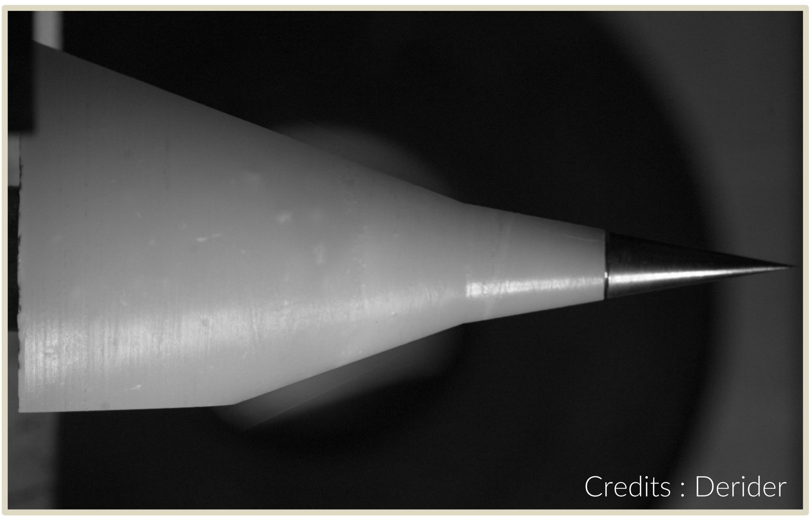


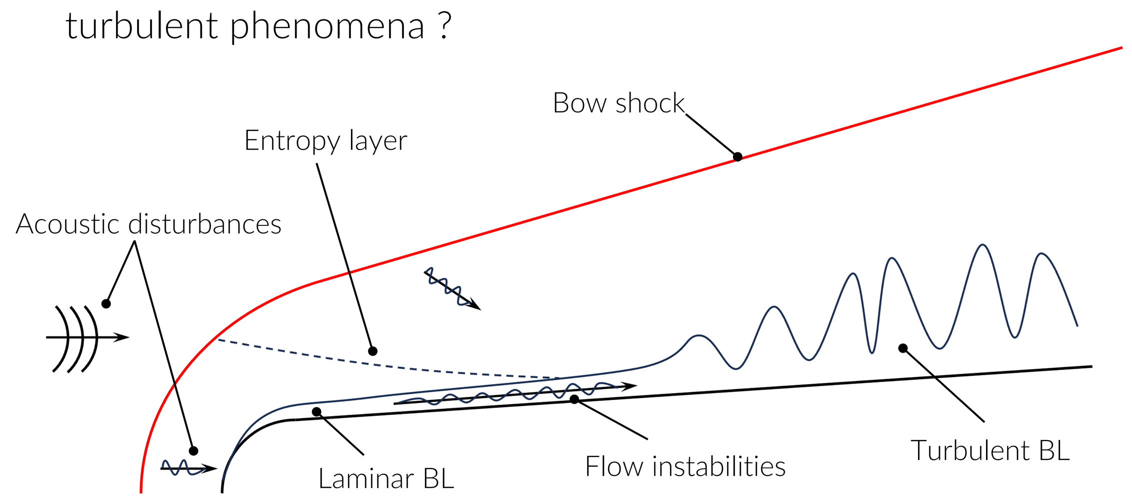
Figure 1. Double wedged sharp cone made in paraffin being tested in the Mach 6 VKI H3 blowdown wind tunnel to study cross-hatching phenomena.

Objectives

Based on a high-order and high-fidelity solver, investigating the effects of acoustic disturbances (i.e. wavelets or shocklets) radiated from the turbulent hypersonic boundary layer on the development of nozzle flows and the laminar to turbulent transition on test models.

Research questions

- To what extent the turbulent weak shock waves, or shocklets, have an influence on the flow expansion ?
- What are the shocklets' impacts on thermal non-equilibrium, and its influence of the vibrational melting ?
- To what extent the noise emanating from noisy hypersonic wind tunnels have an impact on the sample's transition onset ?
- Are high-order solvers capable of robustly capturing hypersonic turbulent phenomena ?



ArgoDG, a high-order discontinuous Galerkin (DG) solver for turbulent flow scale resolving

ArgoDG from Cenaero

- Turbulence modeling (DNS/LES, wall models)
- HPC capabilities (extreme scalability, optimized I/O)
- Mutation++ (thermodynamics, transport and chemistry library)
- Immersed interface
- MAdLib (CAD, curved mesh and adaptation)

High-fidelity DG based solver

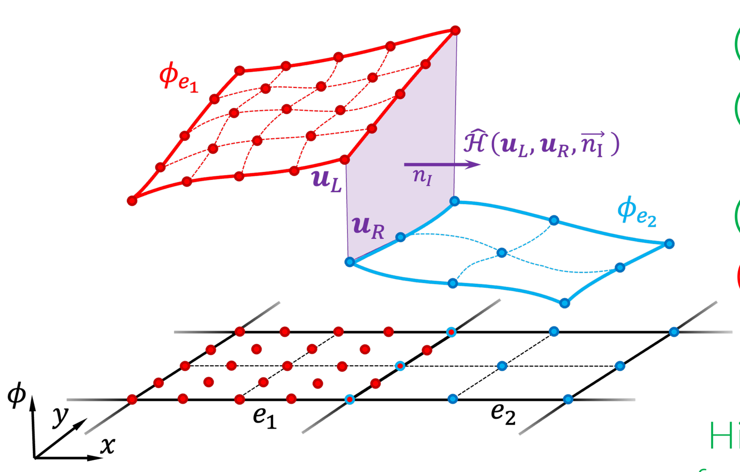
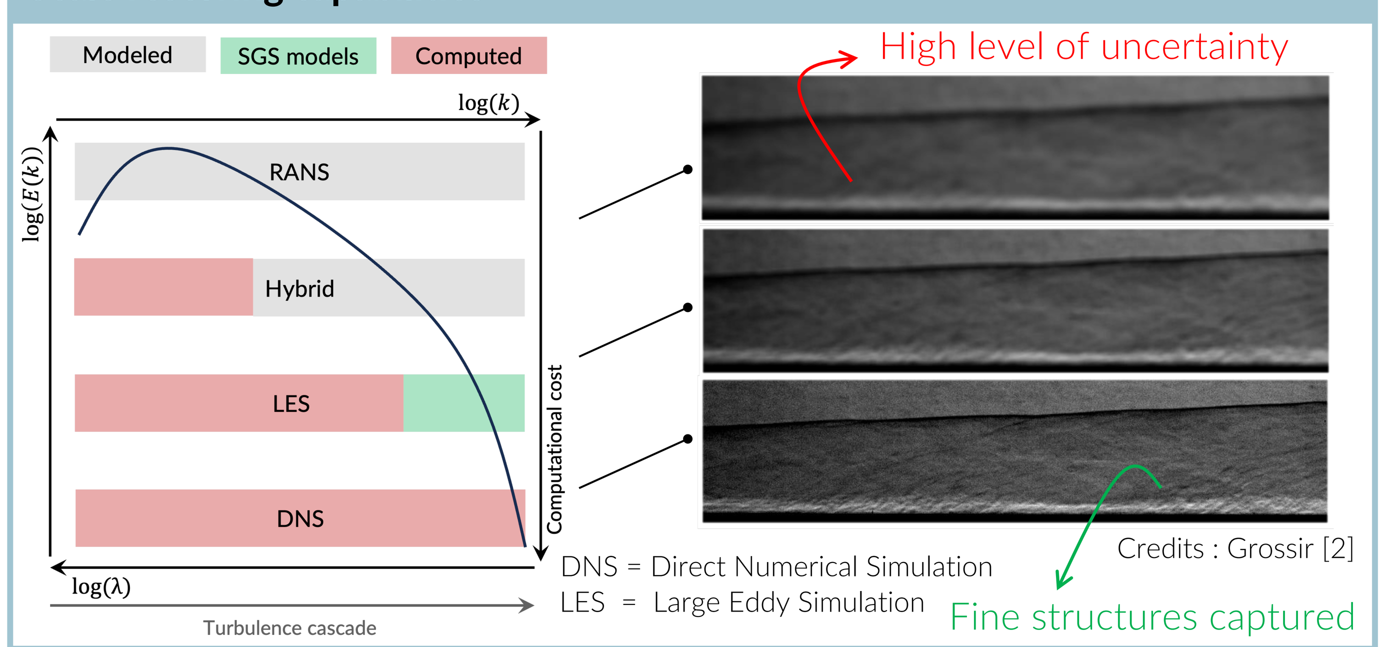


Figure 2. DG representation of two discontinuous elements using a fourth (left) and second (right) order Lagrangian interpolation polynomial in 2D.

- (+) Handling complex geometries
- (+) Local adaptation in mesh size and interpolation order (hp-adaptivity)
- (+) Low dispersion and dissipation
- (-) Lack of robustness for capturing under resolved scales

High-fidelity simulations with fewer degrees of freedom than traditional numerical methods

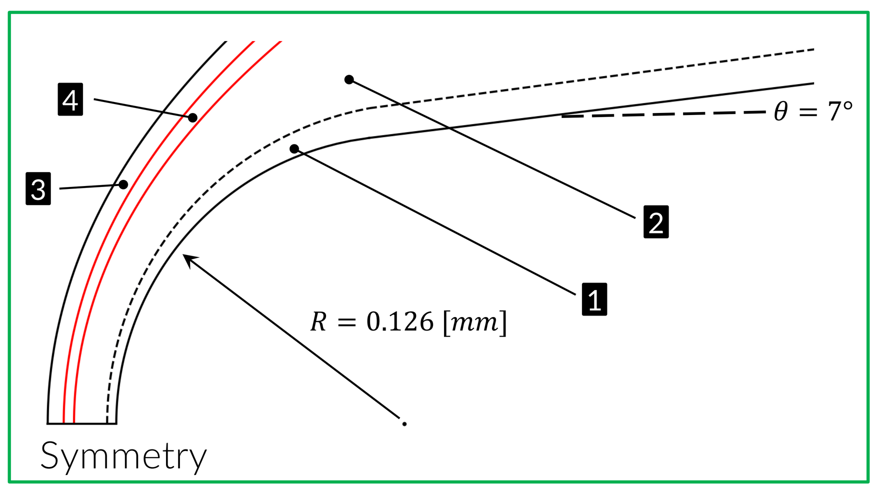
Scale resolving capabilities



DNS = Direct Numerical Simulation
LES = Large Eddy Simulation

Hypersonic boundary layer transition over a blunt cone

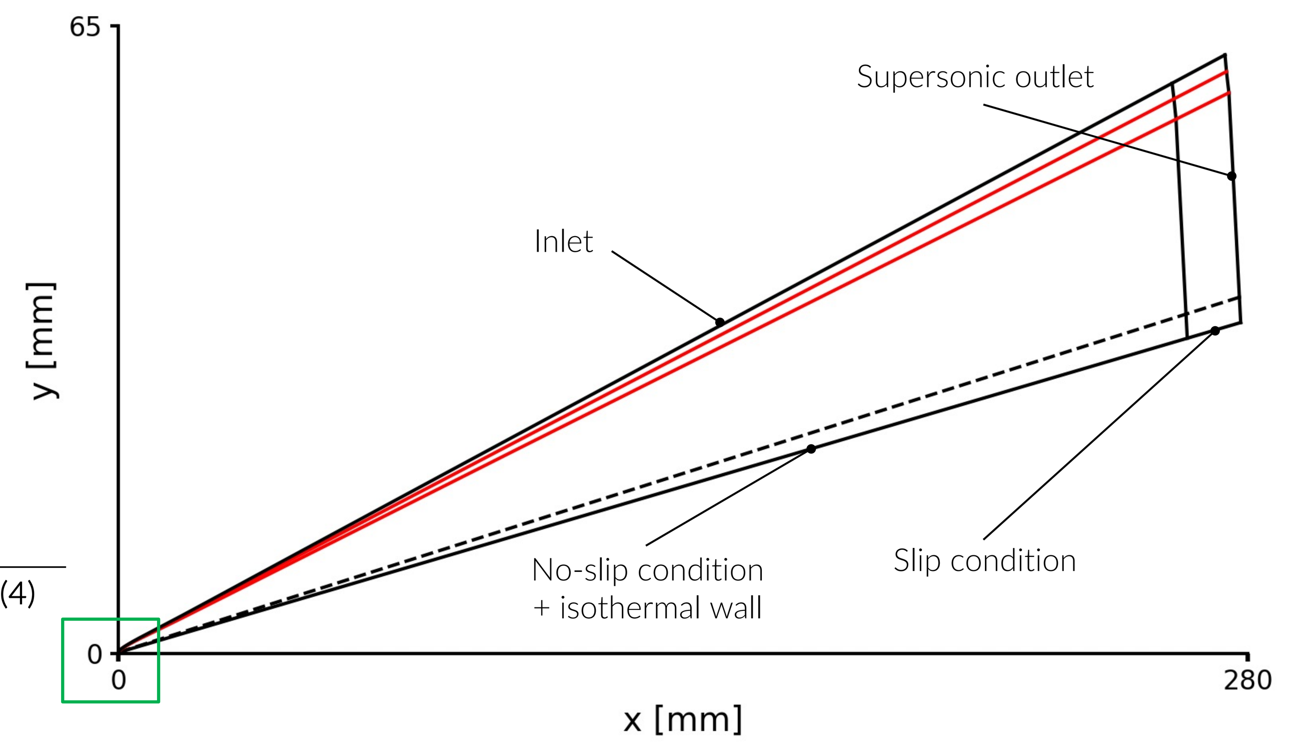
Numerical setup



Numerical strategy :

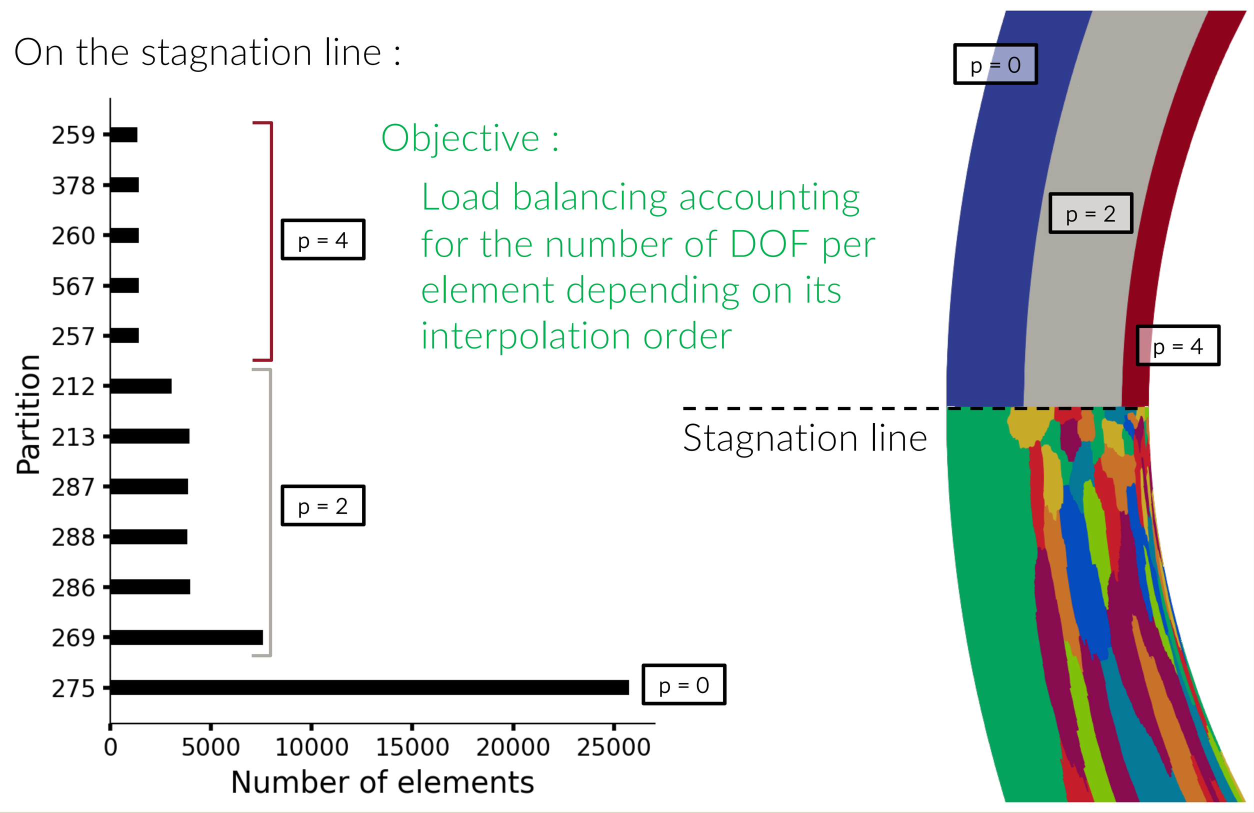
	BL (1)	Post-shock band (2)	Pre- (3) & shock band (4)
Run 1	p = 0	p = 0	p = 0
Run 2	p = 2	p = 0	p = 0
Run 3	p = 4	p = 2	p = 0

re-meshing



Static load balancing

On the stagnation line :



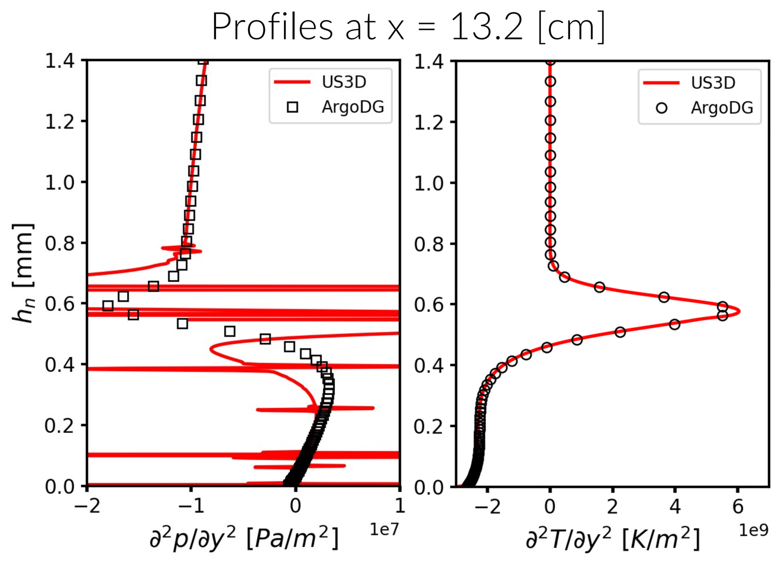
Objective :

Load balancing accounting for the number of DOF per element depending on its interpolation order

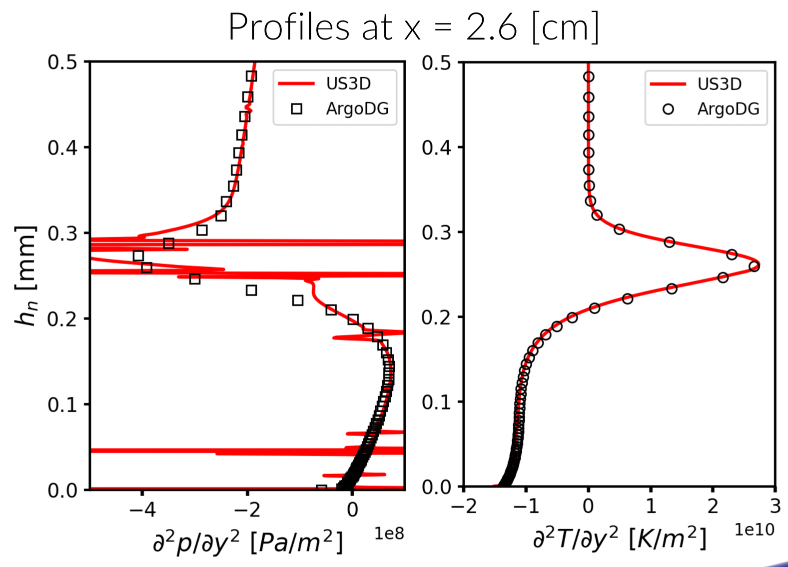
Flow conditions :

$\overline{T_\infty}$ [K]	$\overline{p_\infty}$ [Pa]	$\overline{u_\infty}$ [ms^{-1}]	Ma_∞ [−]	$Re_{\infty,unit}$ [m^{-1}]	T_w [K]
60.98	1358.63	939.63	6	18 ×10^6	295

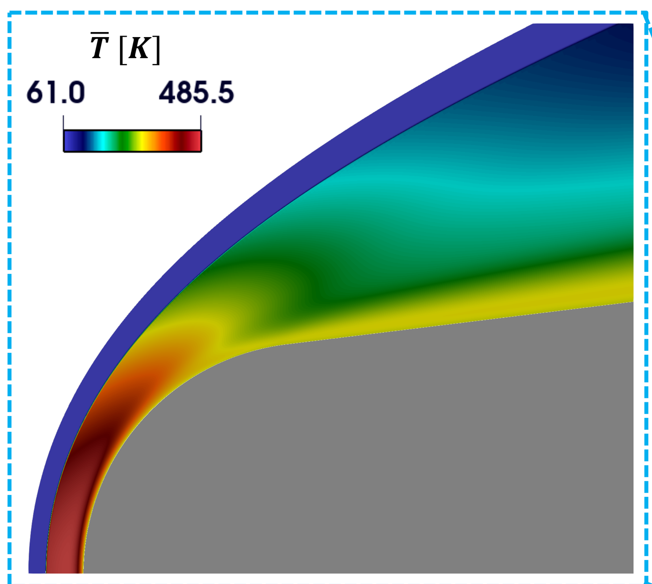
Profiles at x = 13.2 [cm]

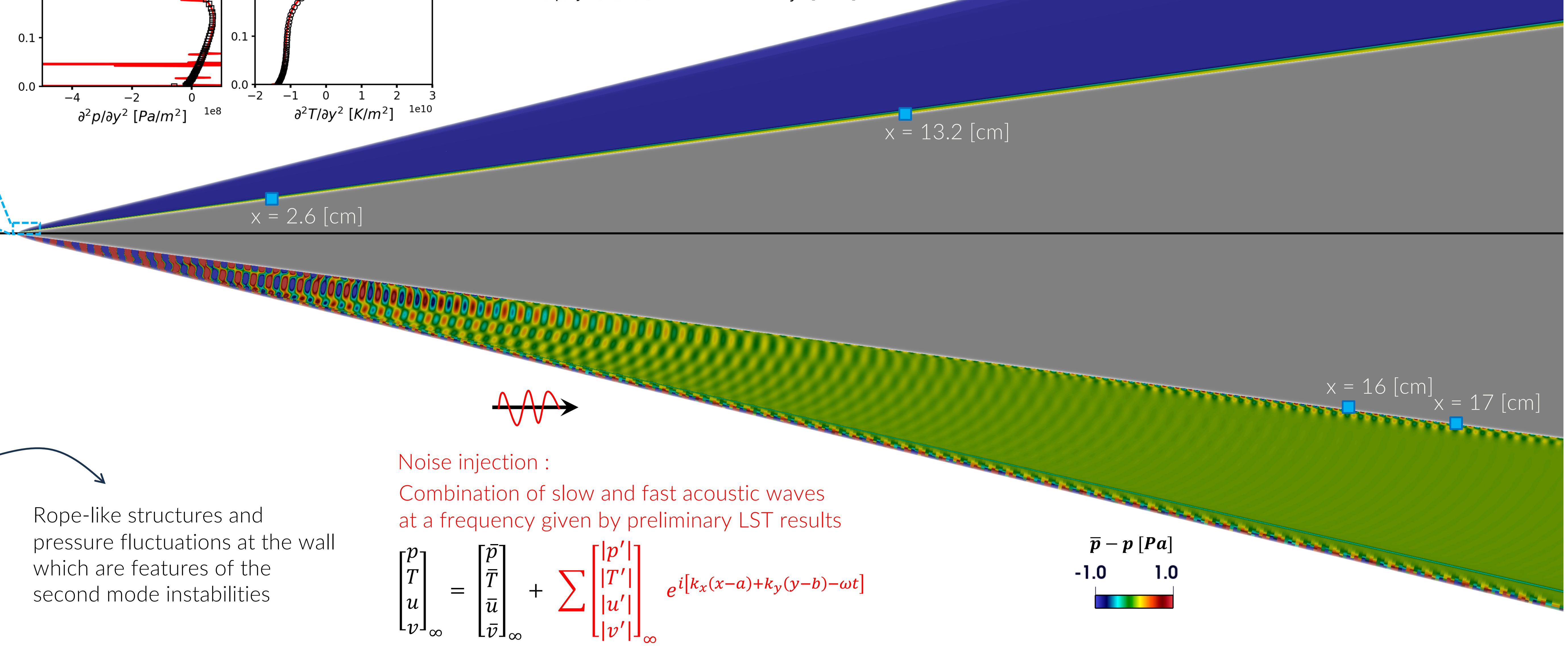


Profiles at x = 2.6 [cm]

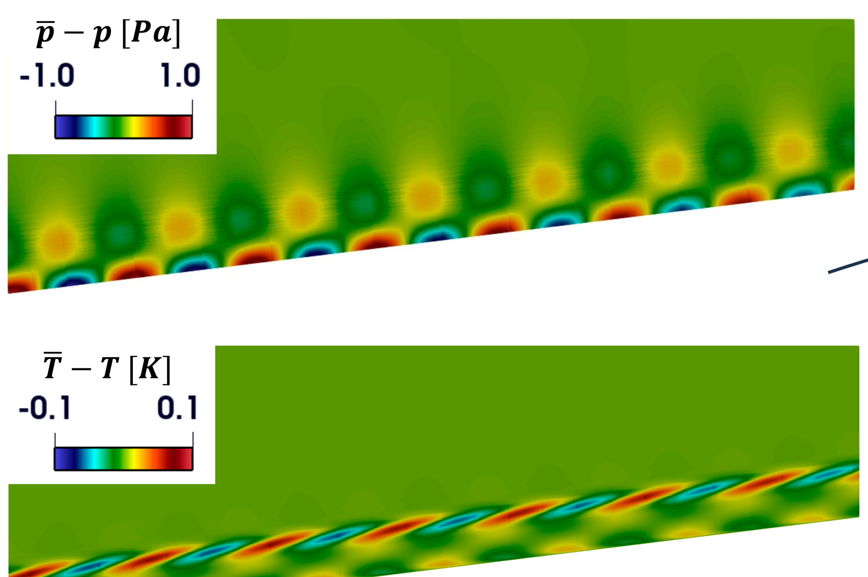


Smooth first and second derivatives are required by Linear Stability Theory solvers (e.g. VESTA [3] from VKI) to perform stability analysis





Temperature and pressure fluctuations along the wall at t = 0.5 [ms] between at x = [16, 17] [cm] :



Rope-like structures and pressure fluctuations at the wall which are features of the second mode instabilities

Noise injection :

Combination of slow and fast acoustic waves at a frequency given by preliminary LST results

$$\begin{bmatrix} p \\ T \\ u \\ v \end{bmatrix}_\infty = \begin{bmatrix} \overline{p} \\ \overline{T} \\ \overline{u} \\ \overline{v} \end{bmatrix}_\infty + \sum \begin{bmatrix} |p'| \\ |T'| \\ |u'| \\ |v'| \end{bmatrix}_\infty e^{i[k_x(x-a)+k_y(y-b)-\omega t]}$$

Reference

[1] Grossir, Guillaume & Masutti, Davide & Chazot, Olivier. (2015). Flow characterization and boundary layer transition studies in VKI hypersonic facilities. 10.2514/6.2015-0578.
[2] Grossir, Guillaume. (2015). Longshot Hypersonic Wind Tunnel Flow Characterization and Boundary Layer Stability Investigations. 10.13140/RG.2.1.2394.0720.
[3] Pinna, Fabio. (2013). VESTA toolkit: a Software to Compute Transition and Stability of Boundary Layers. 43rd Fluid Dynamics Conference. 10.2514/6.2013-2616.

Acknowledgment

This research is part of the Space4ReLaunch project, which is supported by the SPW Economie Emploi Recherche of the Walloon Region, under grant agreement no. 2210181. Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI).