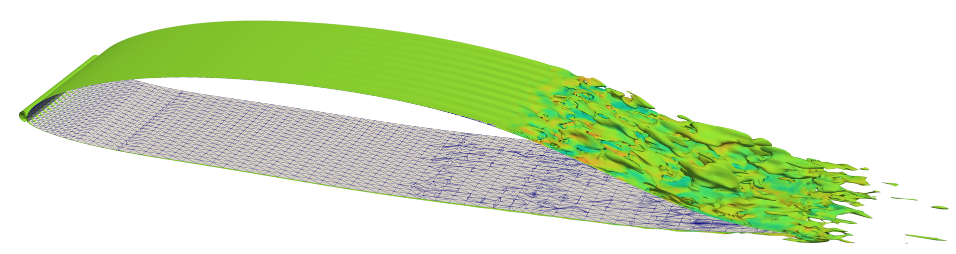
High-fidelity numerical simulations on airfoils at low-Reynolds number

C. Brunelli [1,2,3], B. Janssens [1], B. Marinus [1], G. May [2], M. Runacres [3]
[1] Royal Military Academy, Department of Mechanical Engineering, Brussels, Belgium
[2] Von Karman Institute for Fluid Dynamics, Sint-Genesius-Rode, 1640, Belgium
[3] Vrije Universiteit Brussel, Brussels, Belgium
carlo.brunelli@mil.be

Research Purpose

The request for numeric models for transitional airfoils has grown in the recent years thanks to their emerging applications for high-altitude pseudo-satellites (HAPS). Developing new suitable numerical methods avoids expensive and time-consuming experimental testing and helps to identify promising geometries. For this purpose, the research has developed a new version of the Variational MultiScale method (VMS) - firstly introduced by Hughes2005 [2] - which belongs to the family of implicit Large Eddy Simulation (iLES).
The project ambitiously aims to extend the capability to solve the adjoint problem - leveraging Automatic Differentiation (AD) - to generate airfoils with better performances.



DU89-134 airfoil at Reynolds 500 000 1°, velocity contour, u_z colormap

Low Reynolds regime

HAPS flight conditions:

- High altitude: $16-20km$
- Low-speed: $Mach \approx 0.1$
- Low-Reynolds: $Re \leq 500000$

Developing new suitable numerical methods avoids expensive and time-consuming experimental tests and helps identify promising geometries. The challenges addressed are:

- formation of the Laminar Separation Bubble (LSB)
- laminar to turbulent transition
- Turbulence Intensity (TI) effects

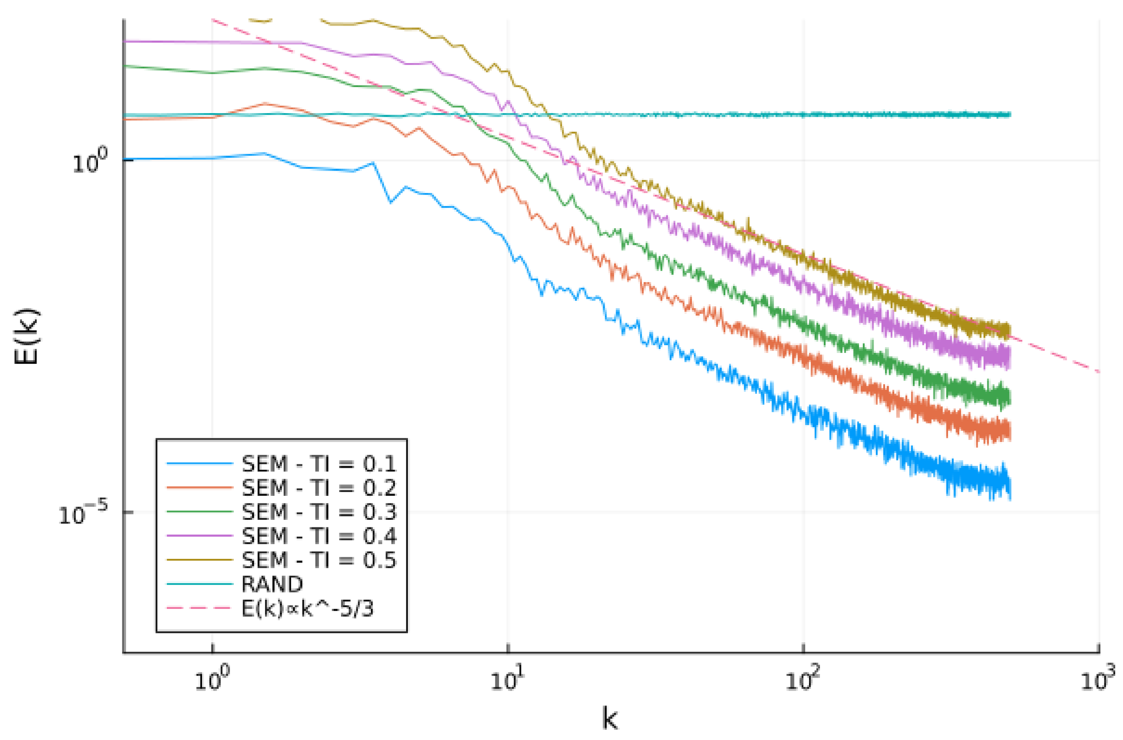
Variational MultiScale Method

A Linearized and Segregated VMS (LS-VMS) has been implemented:

- coded in the Julia programming language
- implicit Large Eddy Simulation (iLES)
- fully 3-dimensional unsteady
- parallelized
- no calibration needed

Synthetic Eddy Method

It produces realistic and coherent turbulent fluctuations, which deeply influence the transition and separation point. It has also been implemented in Julia [1]. Random fluctuations do not produce a realistic flow, and they are quickly dissipated.

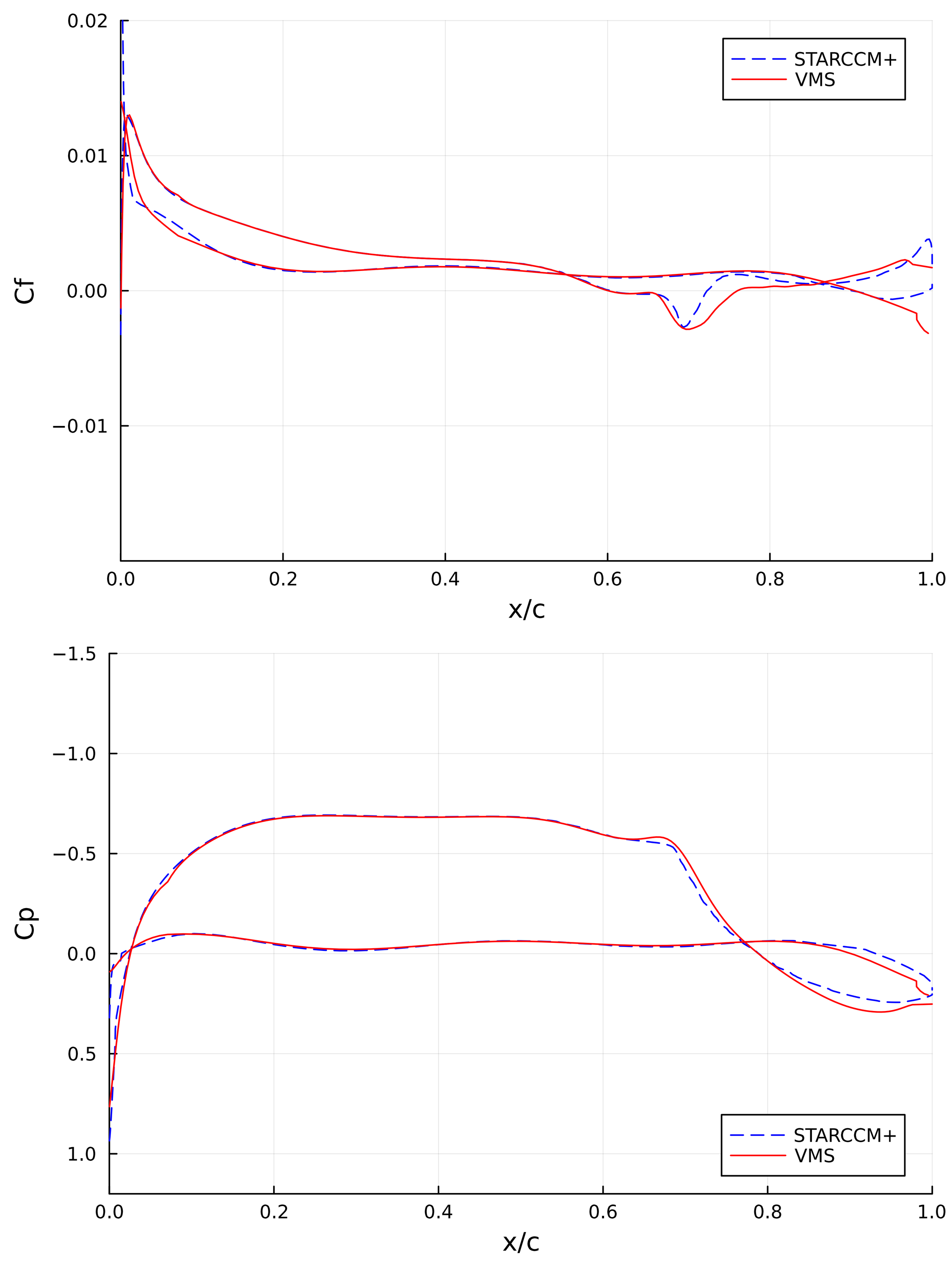


Flowfields energy spectra produced using SEM at different turbulence intensity. Comparison with the random generated fluctuations

Watch a video of an unsteady simulation on YouTube:

Laminar Separation Bubble

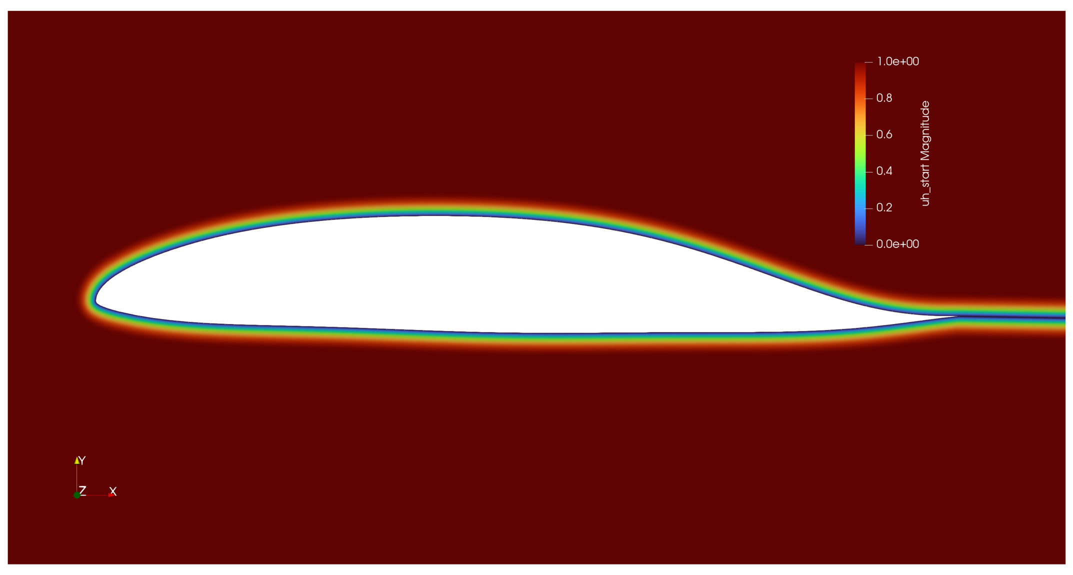
LS-VMS is able to capture the LSB on transitional airfoils. The RANS method, implemented in STARCCM +, uses the transitional model $\gamma - Re_\theta$ which is based on a series of experimental correlations; see [3]. The VMS does not need any previous calibration, experiments, or coefficients to be adjusted.



DU89-134 airfoil at Reynolds 500 000 1° pressure and friction coefficient, RANS and LS-VMS comparison

Boundary Layer Initialization

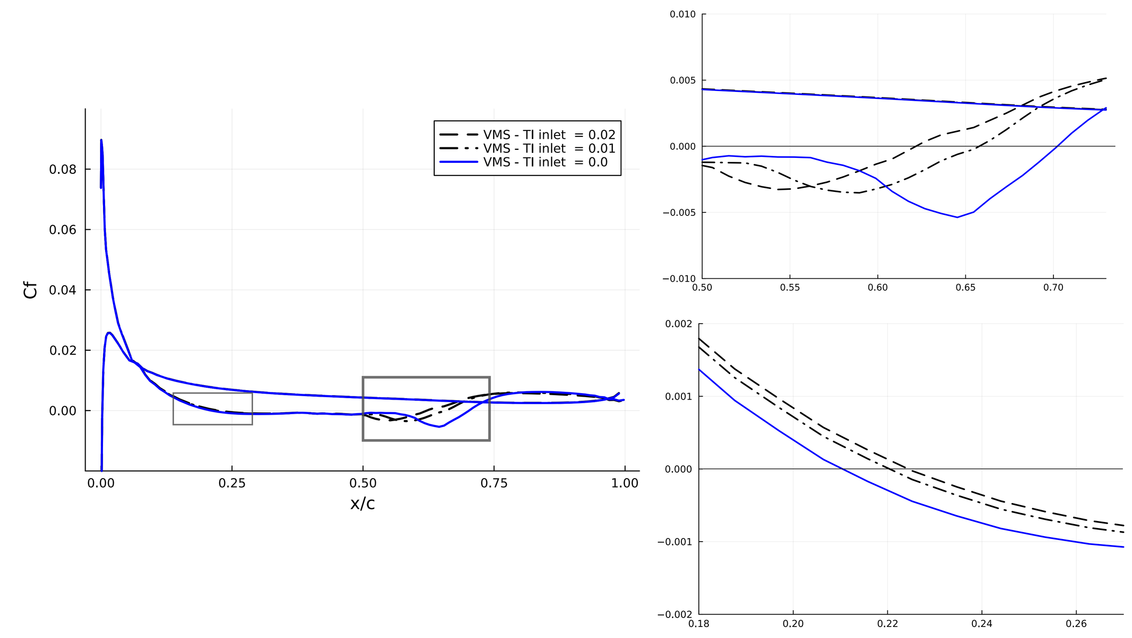
Avoiding high velocity in small cells of the boundary layer in the initial iterations is crucial to avoid instability. Computing the wall distance and then initializing the boundary layer with a quadratic function ensures numerical stability.



Velocity magnitude initialization for DU89-134 airfoil

LSB and Turbulence Intensity

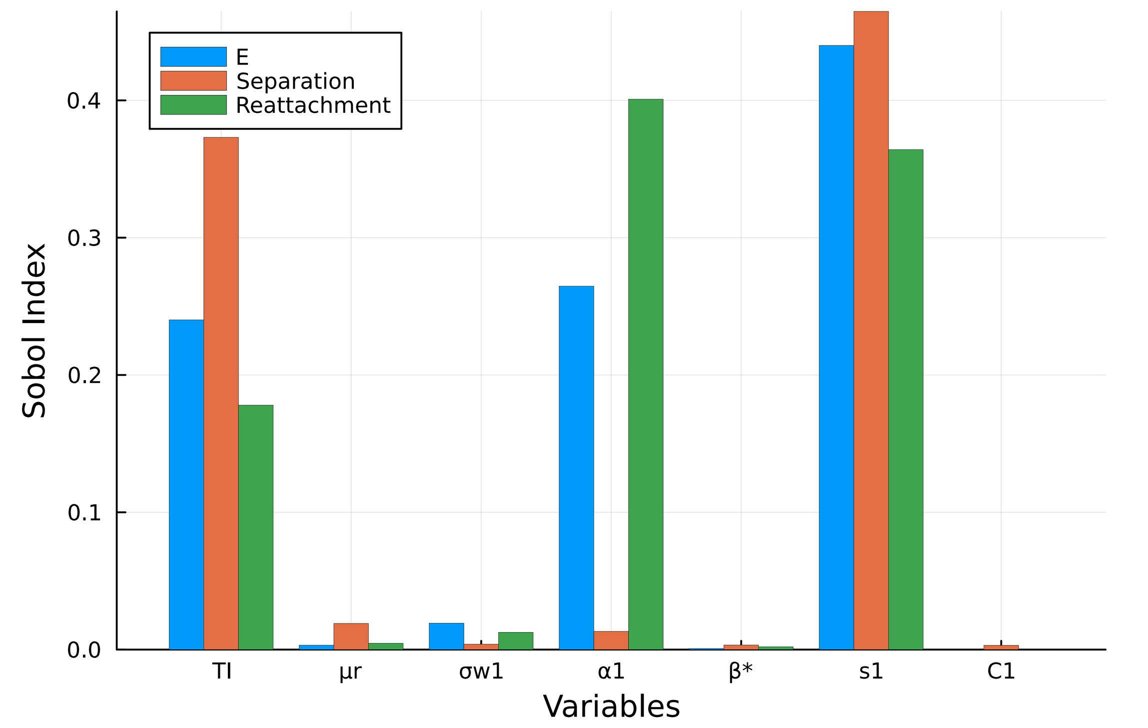
LSB is deeply affected by free-stream TI. This parameter can be used as an independent variable to tune the results and better match them with experiments.



Friction coefficients at different TI for SD7003 airfoil at Reynolds 60 000 at 4°

Uncertainty Quantification

UQ is used to assess the confidence interval of CFD results and identify the closure parameters that most influence the solution.



Sobol indexes for different parameters for SD7003 airfoil at Reynolds 60 000 at 4°

Industrial partner

Collaboration with *STRATOS solution, Belgium*, for the in-flight test in the stratosphere.

[1] Carlo Brunelli. Syntheticeddymethod.jl: A julia package for the creation of inlet flow conditions for les. *Journal of Open Source Software*, 8:5565, 7 2023.

[2] Thomas J R Hughes, Victor M Calo, and Guglielmo Scovazzi. *Variational and Multiscale Methods in Turbulence*. Springer, 2005.

[3] Galen B Schubauer and Harold K Skramstad. Laminar boundary-layer oscillations and transition on a flat plate 1, 1947.