Near stall simulation of the flow around an airfoil using a zonal RANS/LES coupling method

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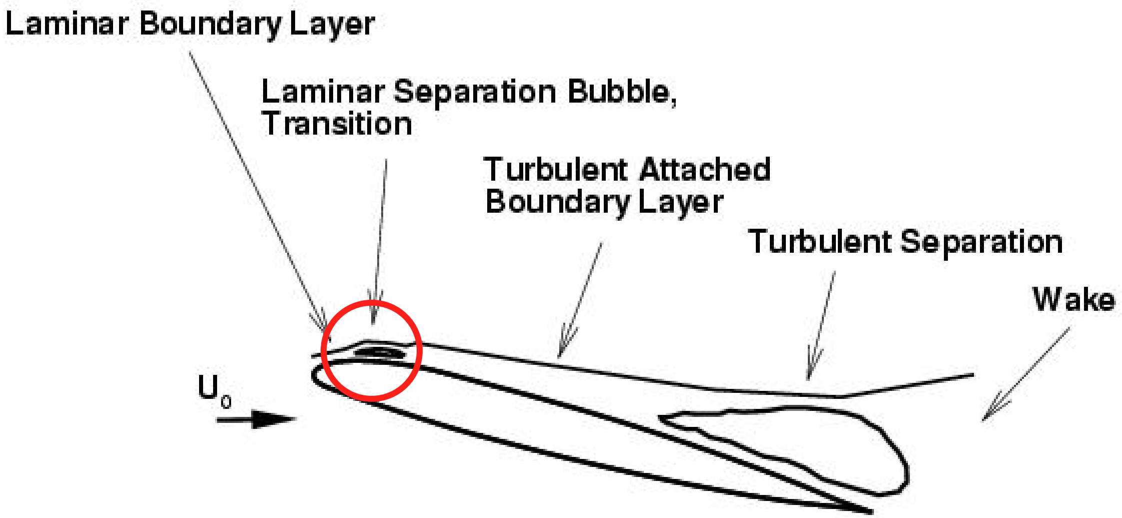
Outline

- **Context**
- **Numerical Method**
- **Reference results (LES)**
- **Zonal RANS/LES results**
- **Conclusions and follow on activities**

Context

Reasons which may lead to the massive flow separation of stall:

- Increase of the turbulent separation at the trailing edge.
- Breakdown of the laminar separation bubble **(LSB)** at the leading edge.
- Interaction between the turbulent and the laminar separations.



Boundary layer evolution on the suction side of an airfoil at high angle of attack.

⇨ **LSB** is a crucial parameter for the stall phenomenon

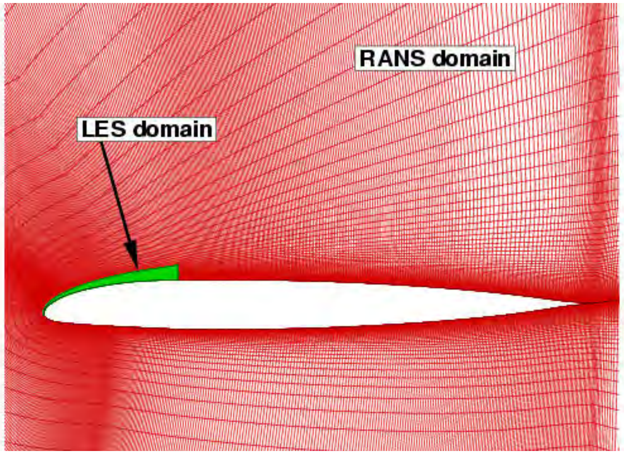
Context

RANS approach does not predict accurately the stall occurrence:

→ not designed for simulating transition

Zonal RANS/LES coupling method in order to:

- Combine: - LES for the LSB,
  - RANS for the turbulent boundary layer.



- Have a numerical data base of this flow without the experimental constraints of wall effects.

- Helpful information for the improvement of the the transition and the intermittence models.

Numerical Method

FLU3M solver:

Cell-centered finite volume technique and structured multi-blocks meshes

Coupling Method:

- Zonal RANS/LES coupling method with overlapping RANS and LES domains.

("RANS eddy viscosity reconstruction from LES flow field for turbulent boundary layers" G. Nolin et al., AIAA paper 2005)

Closure Models:

RANS domain: Spalart -Allmaras
LES domains: selective mixed scale (Lenormand *et al.*)

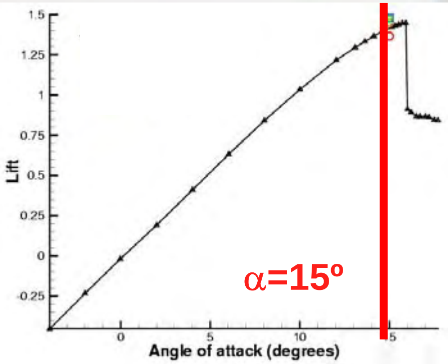
Discretisation:

Space discretisation:	2nd order accurate hybrid upwind/centred scheme
Time discretisation:	2nd order Gear scheme
	Approximate Newton method
	Lower-Upper Symmetric Gauss-Seidel implicit method

Numerical Method

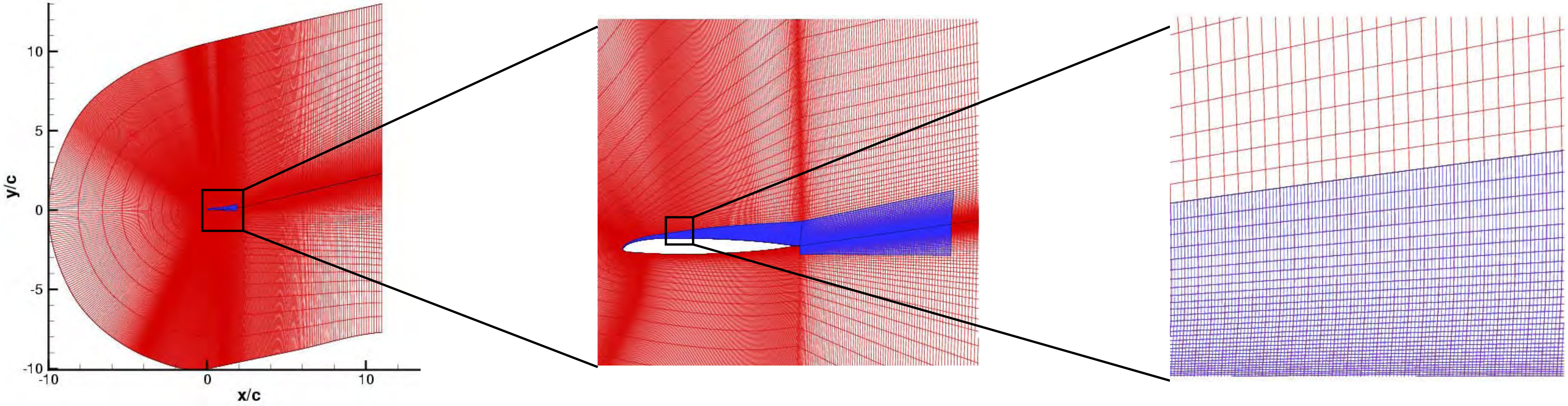
Flow configuration:

Airfoil profile:	OA209
Chord:	c=0.5 m
Reynolds number:	Re=1.83 10^6
Mach number:	M=0.16
Angle of Attack:	α=15º



Calculation and mesh parameters:

	Δt (s)	CPU (h)	N_{pts}(RANS)	N_{pts}(LES)
Mesh M1	**1.5 10^{-7}**	**4000**	**1153x101**	**9.9 M**
Mesh M2	**1.3 10^{-7}**	**5000**	**1259x101**	**12 M**

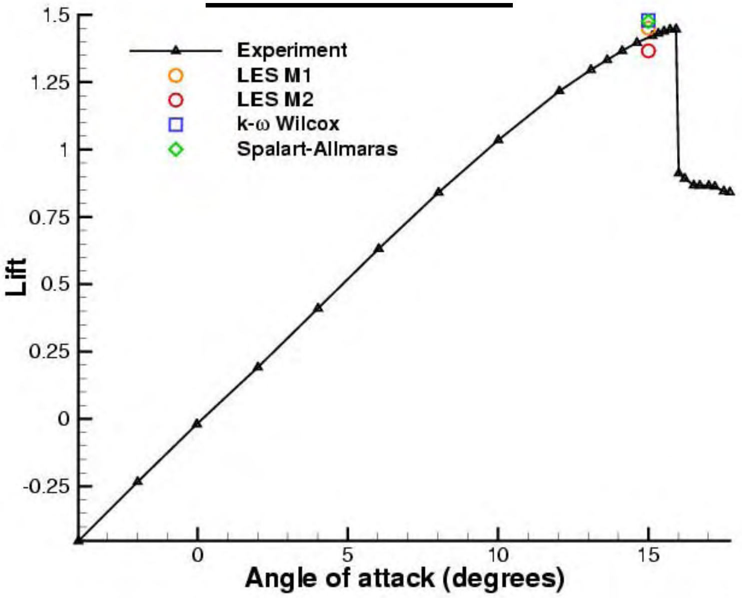


Grid resolution:

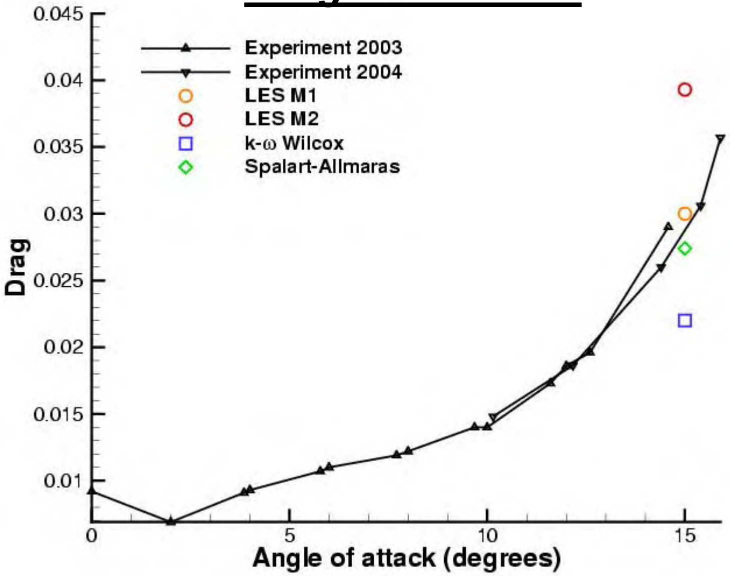
	$\Delta x+$	$\Delta y+$	$\Delta z+$
Mesh M1	**<70**	**<2**	**<20**
Mesh M2	**<50**	**<2**	**<20**

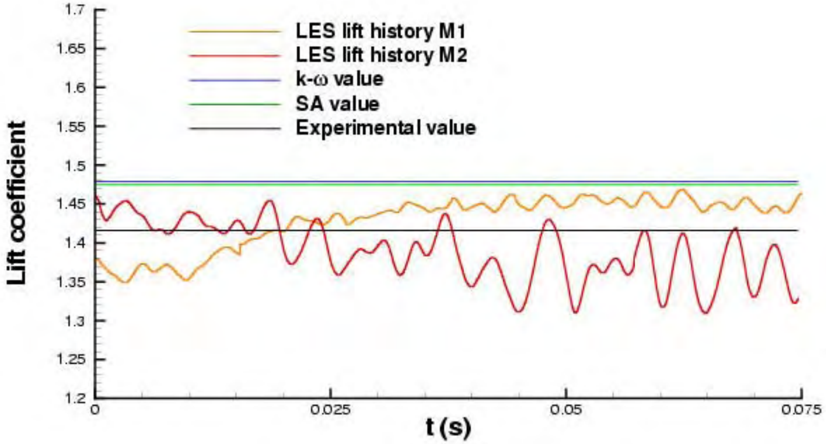
LES Results

Lift coefficient:

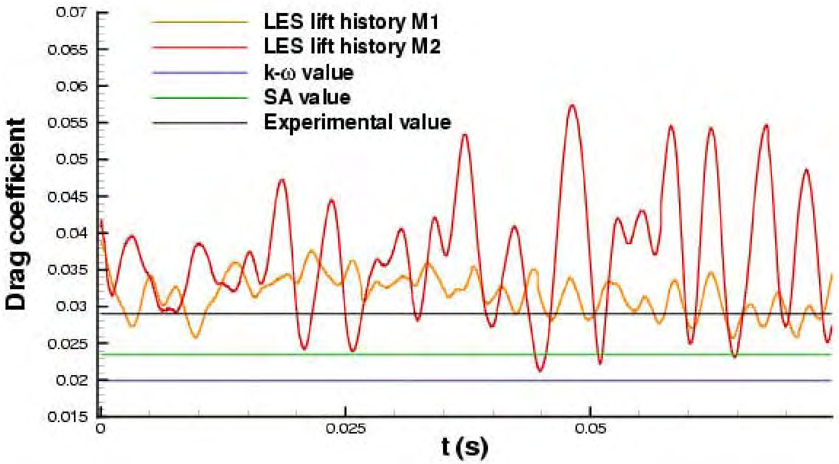


Drag coefficient:





Lift coefficient history



Drag coefficient history

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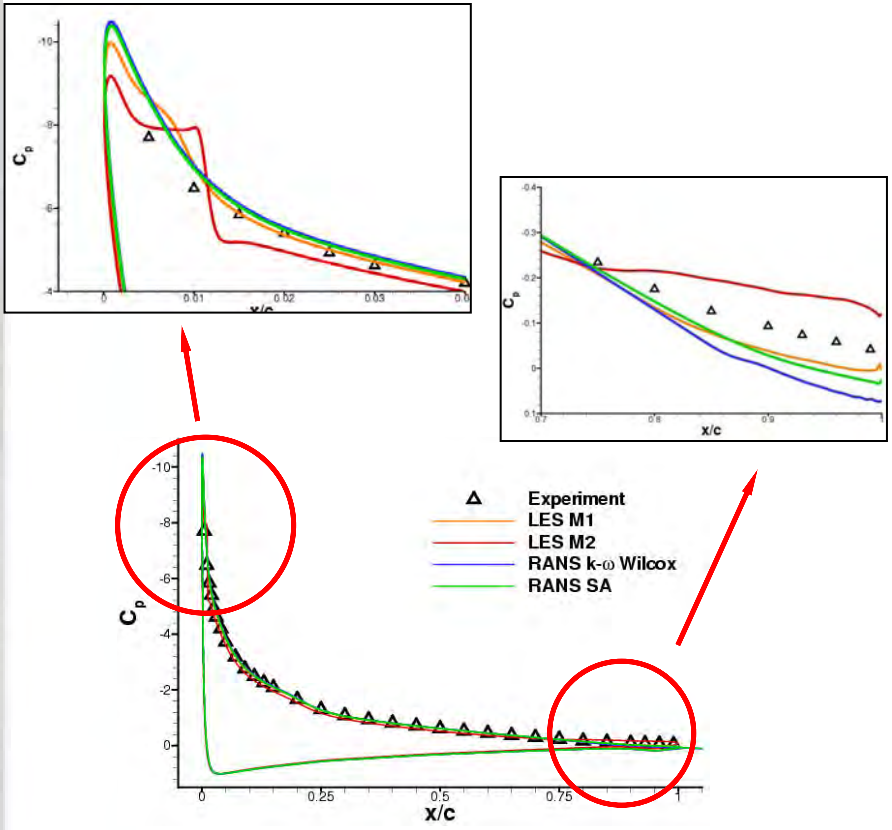
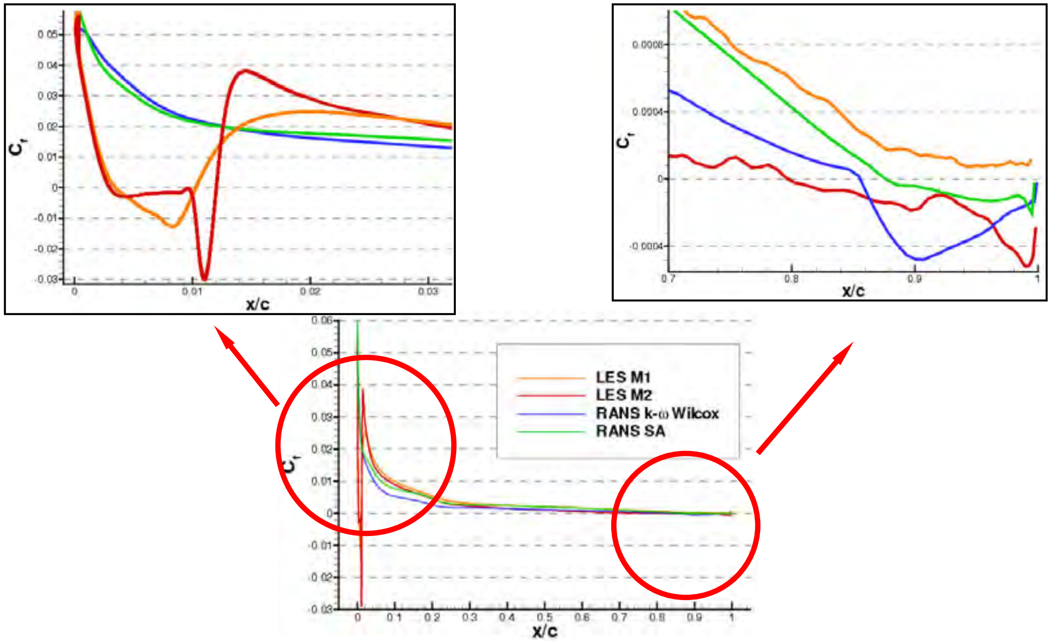
LES Results

Pressure distribution



- Good agreement between LES, RANS and experimental C_p distributions.
- Flattened shape of the LES C_p distribution, characteristic of a LSB.

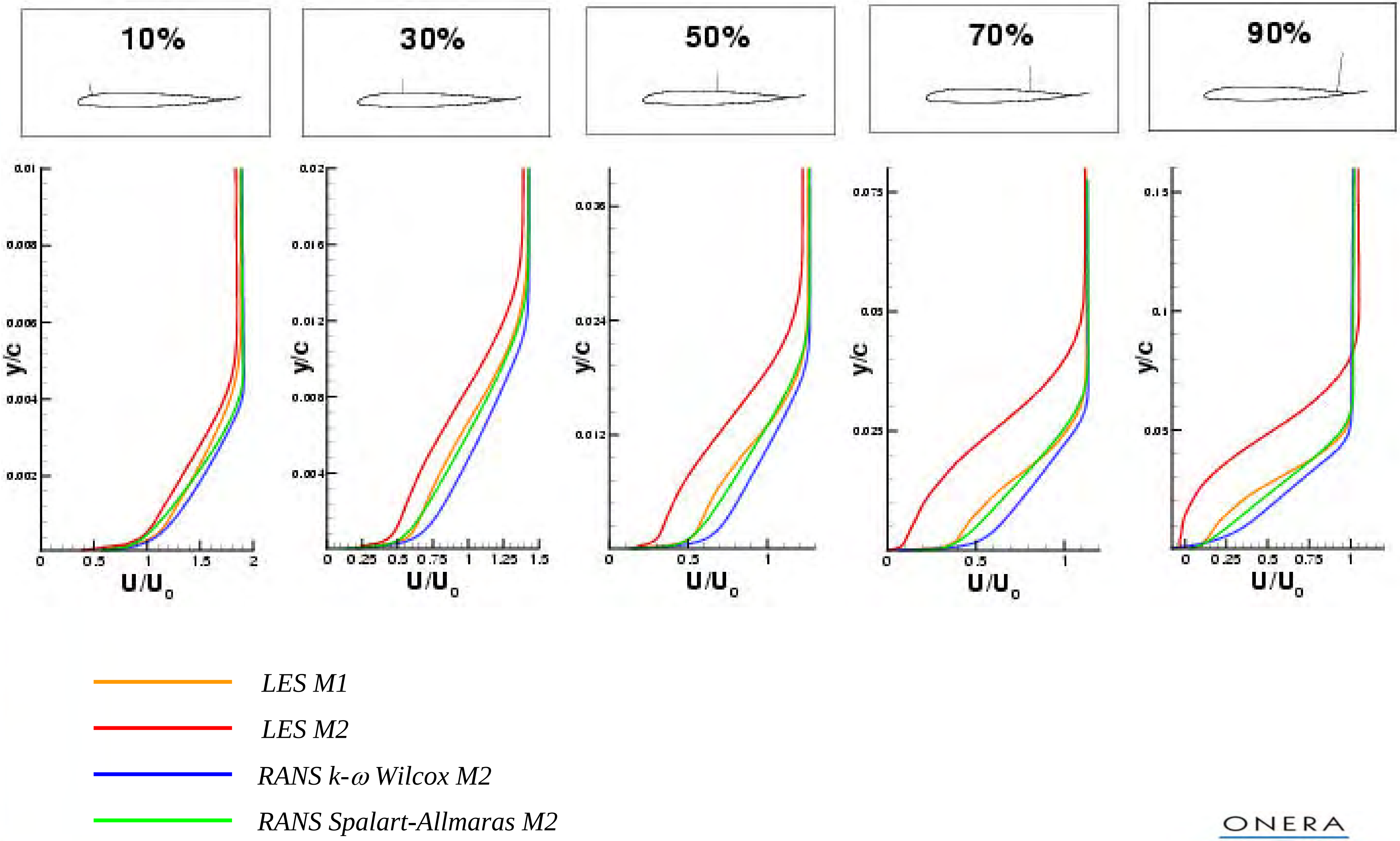
Skin friction distribution



- LSB at the leading edge:
  - 0.95% of chord (LES M1),
  - 1.27% of chord (LES M2),
- Turbulent separation at the trailing edge:
  - 0% of chord (LES M1),
  - 20.5% of chord (LES M2),
  - 14% of chord (RANS k-ω Wilcox),
  - 12% of chord (RANS Spalart-Allmaras).

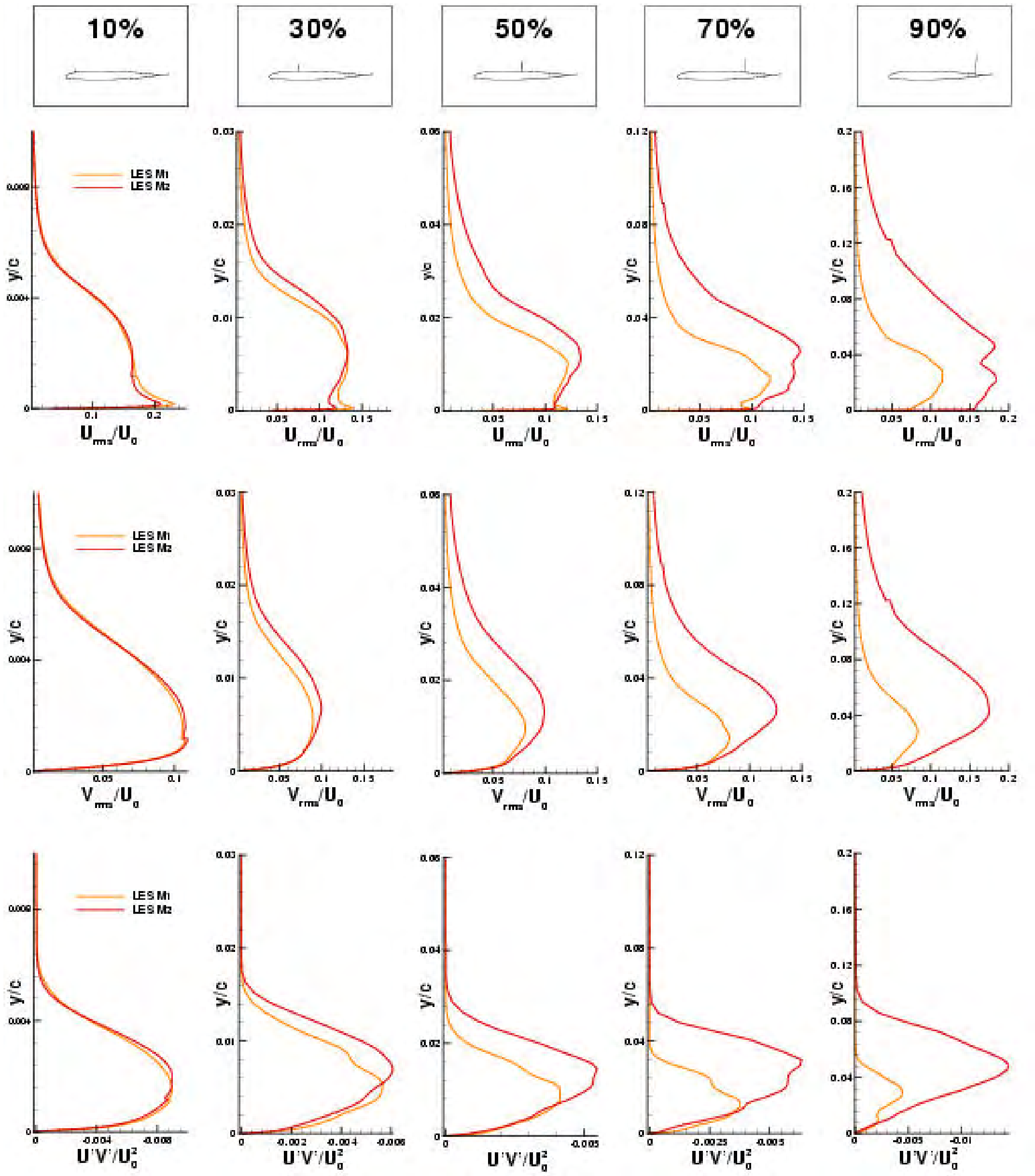
LES Results

Mean velocity profiles



LES Results

Root Mean Square velocity profiles



U_{rms}/U_0

V_{rms}/U_0

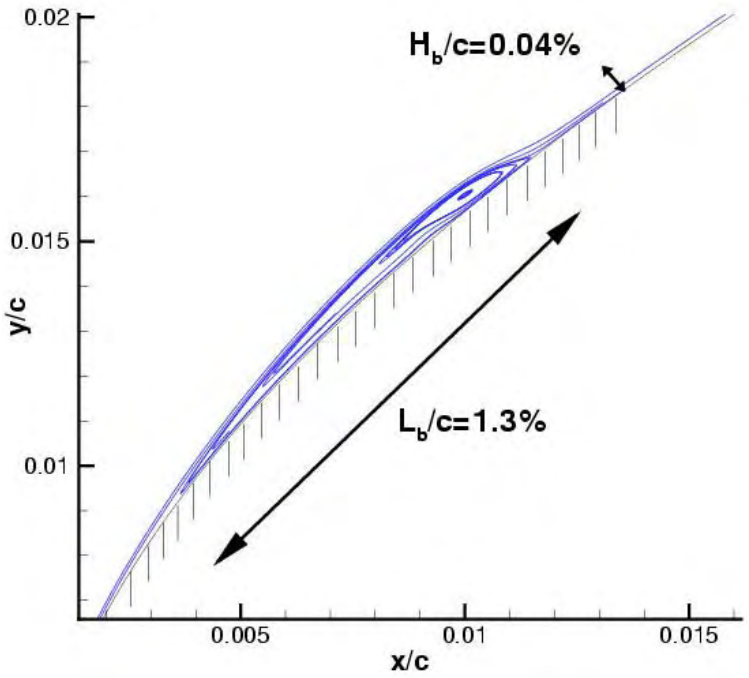
$U'V'/U_0^2$

LES M1

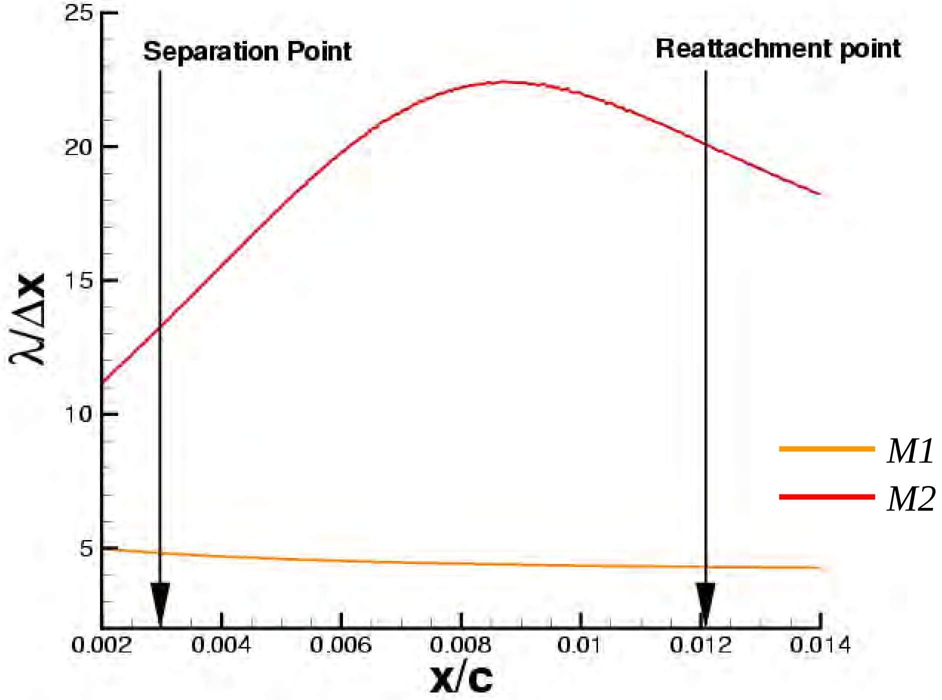
LES M2

Analysis of the transition (LES M2 grid)

Laminar separation bubble size and location



LSB streamlines (LES M2)

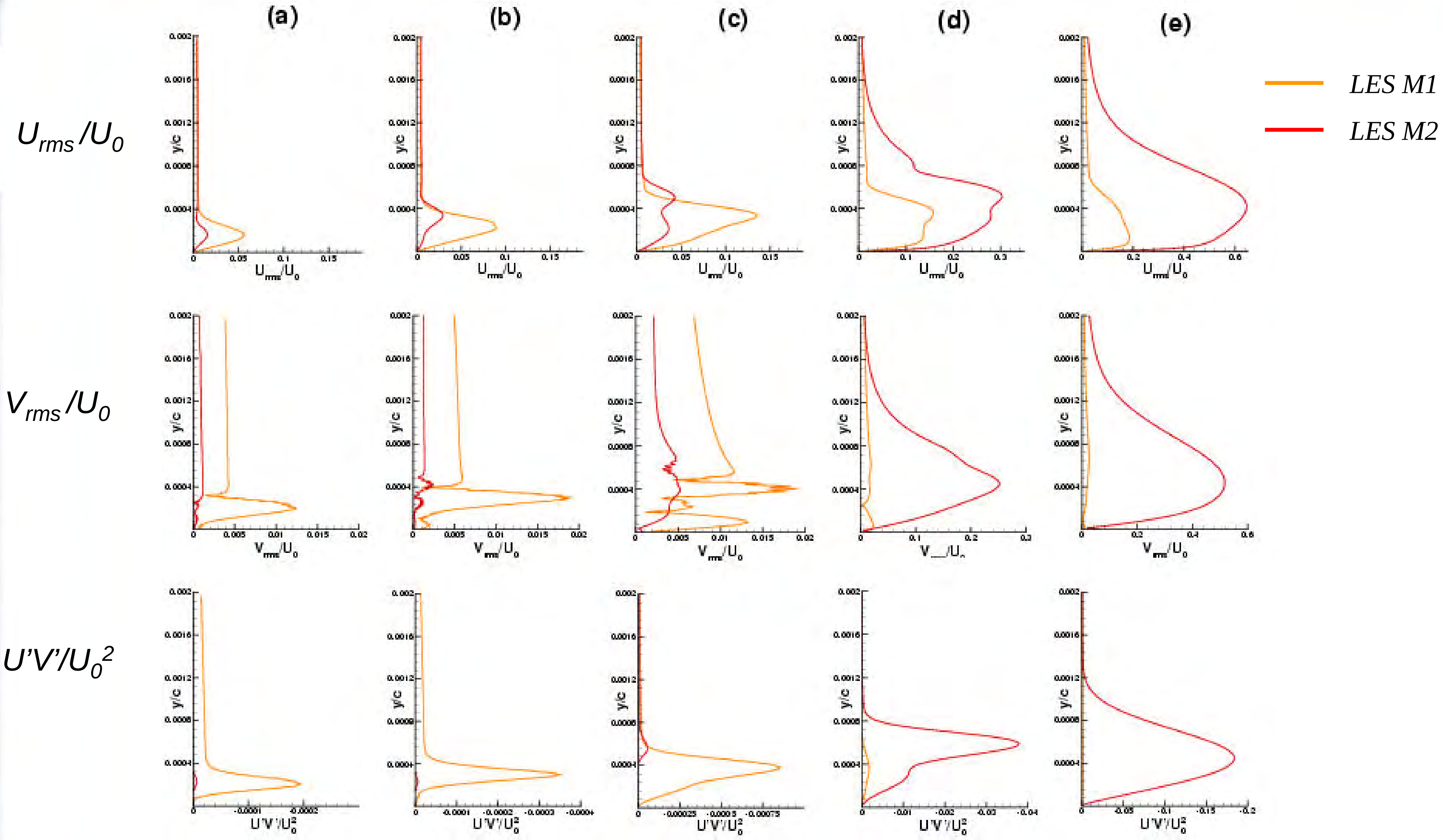


Mesh resolution in the LSB

	Length	Height	Nx	Ny	Nx/λ
Mesh M1	**0.95%**	**0.02%**	**30**	**30**	**3-5**
Mesh M2	**1,27%**	**0.04%**	**160**	**40**	**12-23**

Analysis of the transition (LES M2 grid)

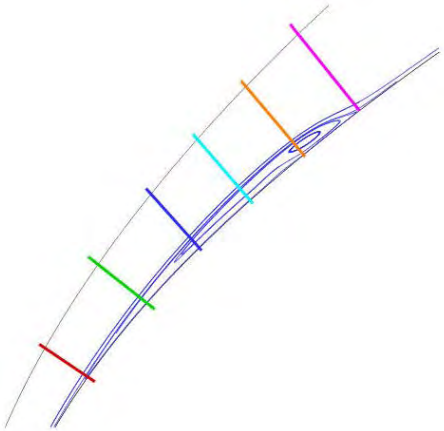
Analysis of the rms fluctuation profiles in the LSB



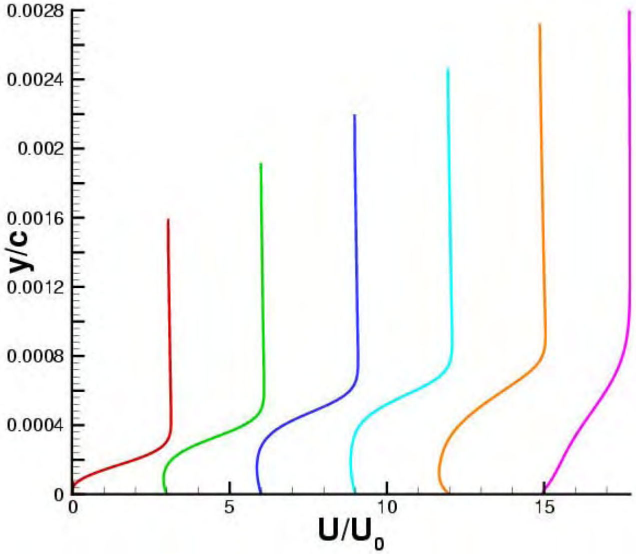
(a) at the separation point, (b) at 25% of the LSB length, (c) at 50% of the LSB length, (d) at 75% of the LSB length, (e) at the reattachment point.

Analysis of the transition (LES M2 grid)

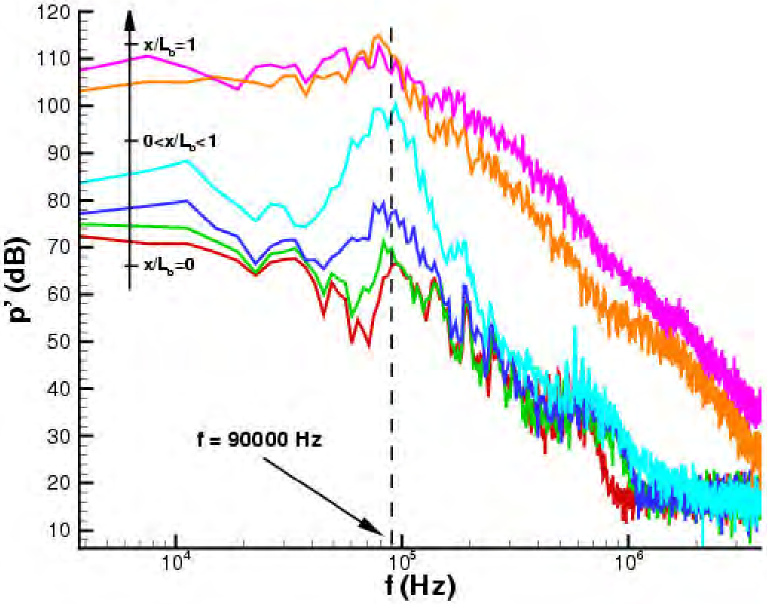
Fourier analysis of the pressure signal



Location of 6 stages in the bubble



Mean velocity profiles at the 6 stages

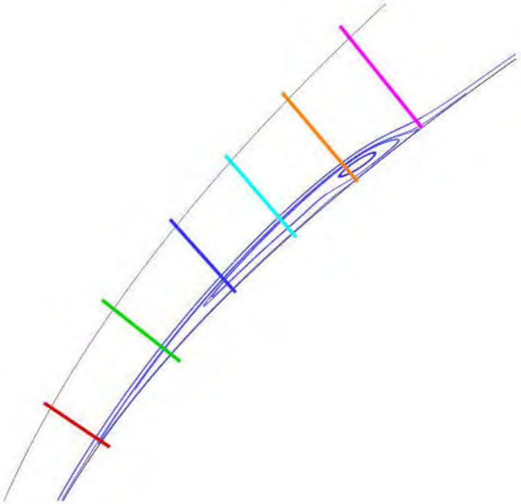


Pressure spectrum at the 6 stages

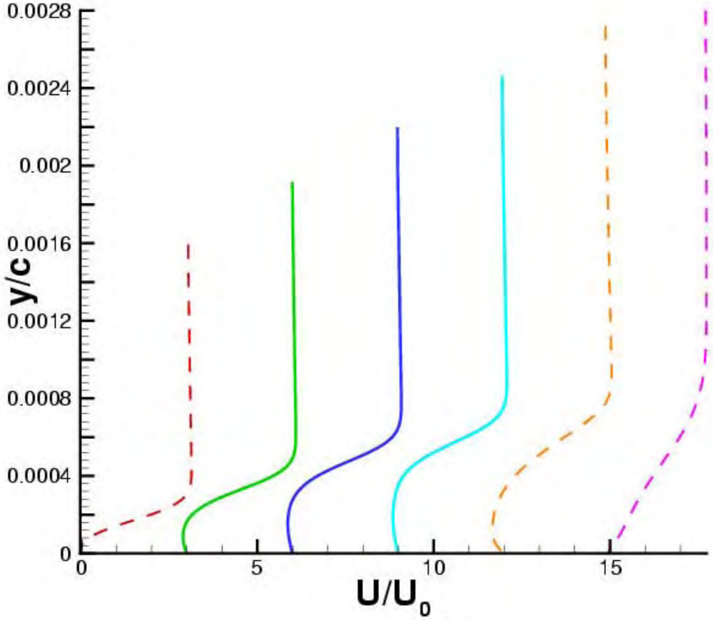
- The numerical truncation errors introduce some disturbances into the laminar flow.
- The unstable velocity profile in the LSB selects a particular frequency
- The value of the selected frequency is: **f=90000 Hz**.

Analysis of the transition (LES M2 grid)

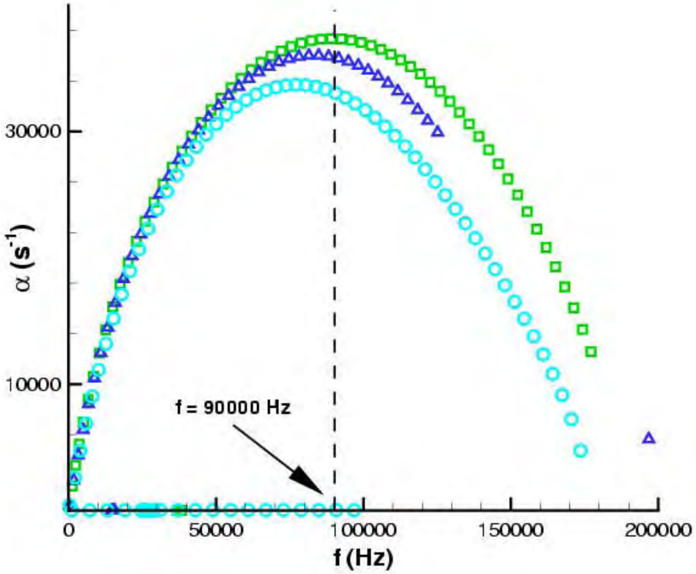
Temporal linear stability analysis of the mean flow



Location of 6 stages in the bubble



Mean velocity profiles at the 6 stages



Temporal stability analysis of 3 mean velocity profiles in the separation bubble

3 mean velocity profiles in the LSB are considered as basic flows.

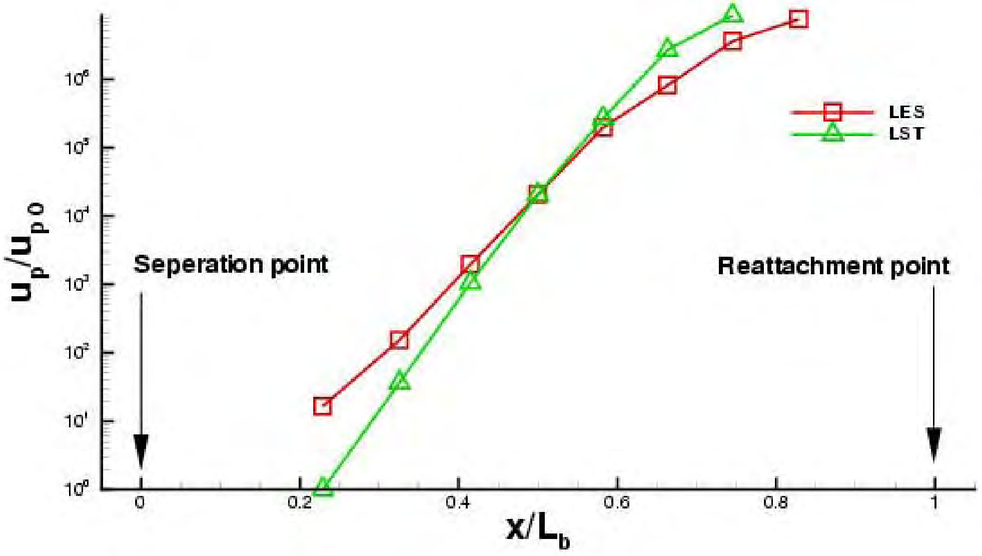
Then $\omega = 2\pi f + i\alpha$ is computed for different values of the real wave number k.

According to the temporal linear stability analysis at these mean velocity profiles,

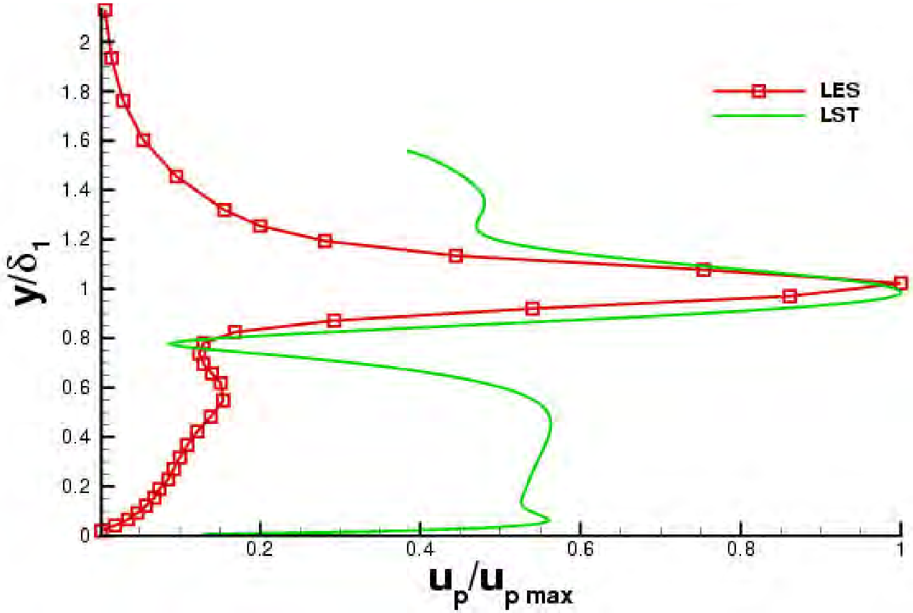
- the flow is unstable ($\alpha>0$)
- the most unstable frequency is **80000 Hz< *f* <90000 Hz**.

Analysis of the transition (LES M2 grid)

Spatial linear stability analysis of the mean flow



Amplification of most unstable 2D mode in the LSB



Most unstable eigenmode shape in the LSB

spatial growth rate:

- General good agreement.
- Lower value of the LES growth rate may be due to:
  - numerical dissipation,
  - interaction with other modes.

Eigenmode shape:

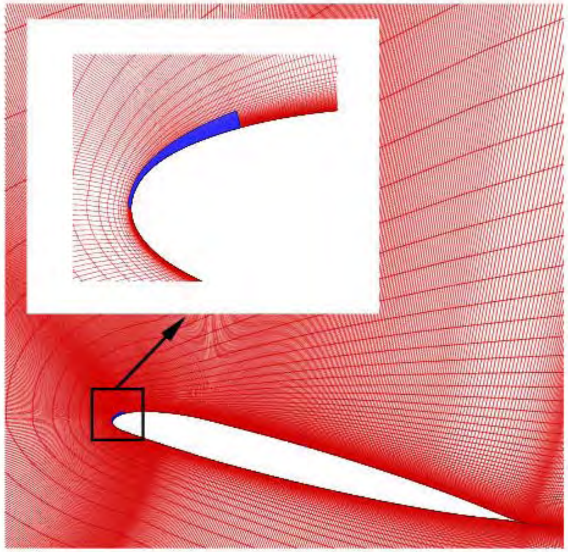
- Good agreement in the inflectional region.
- Discrepancy in the near wall region may be due to the strongly non-parallel flow.

Zonal RANS/LES results

Motivations of a zonal RANS/LES coupling simulation

- **Conclusion of the analysis of the LES:**
  → Important effect of the LSB, at the leading edge, on the downstream boundary layer

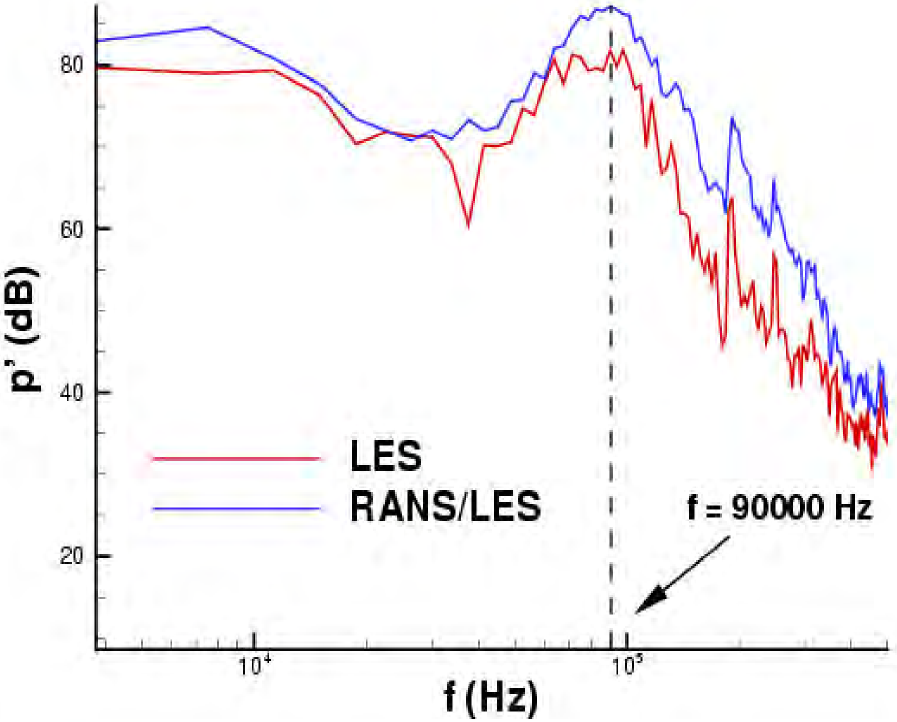
- **Motivations:**
  → Achieve a zonal RANS/LES coupling simulation with a LES domain located in the LSB
  → Compare to a full RANS simulation



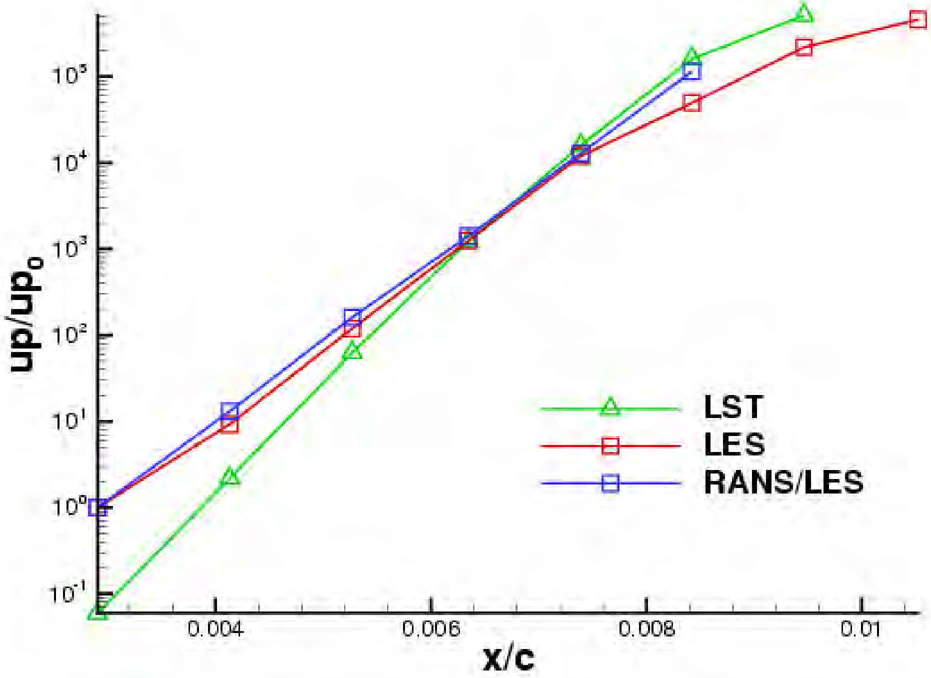
- Reduced LES domain
- Grid resolution identical to M2

Zonal RANS/LES results

Analysis of the transitional flow



LES and RANS/LES pressure spectra in the LSB



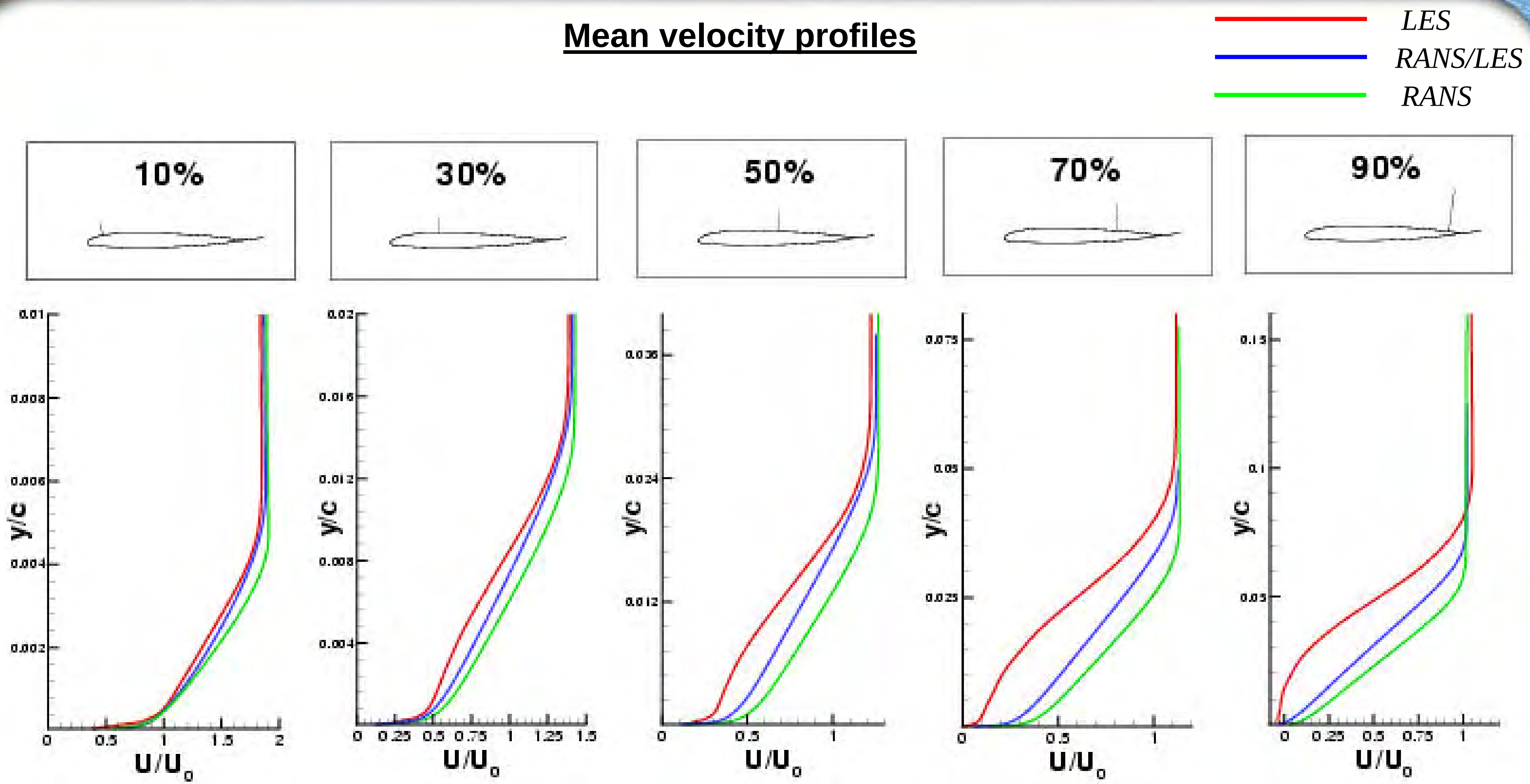
Spatial evolution of the most unstable mode

- Same value of the most unstable frequency
- Same spatial growth rate
- Higher value of this disturbance's amplitude at the separation point

⇨ Same transitional mechanism as the reference LES

Zonal RANS/LES results

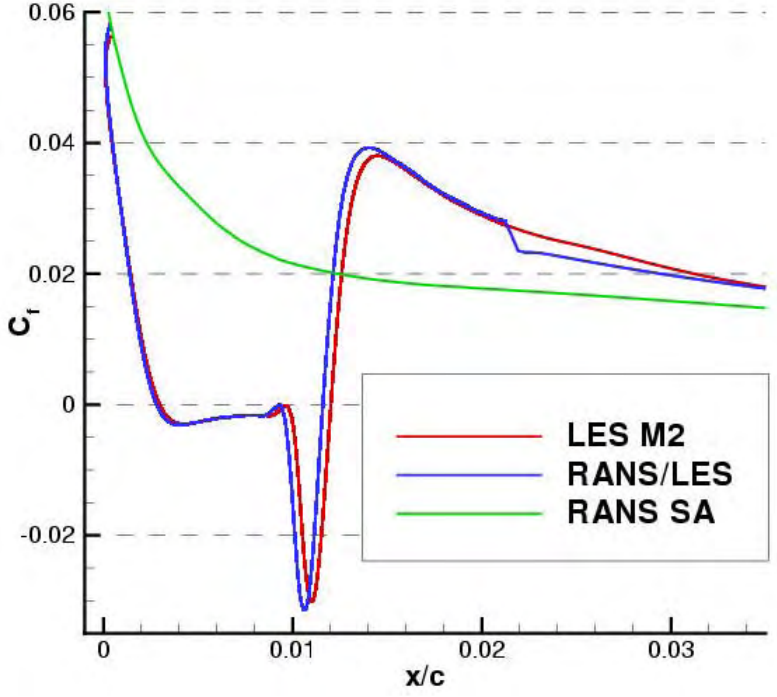
Mean velocity profiles



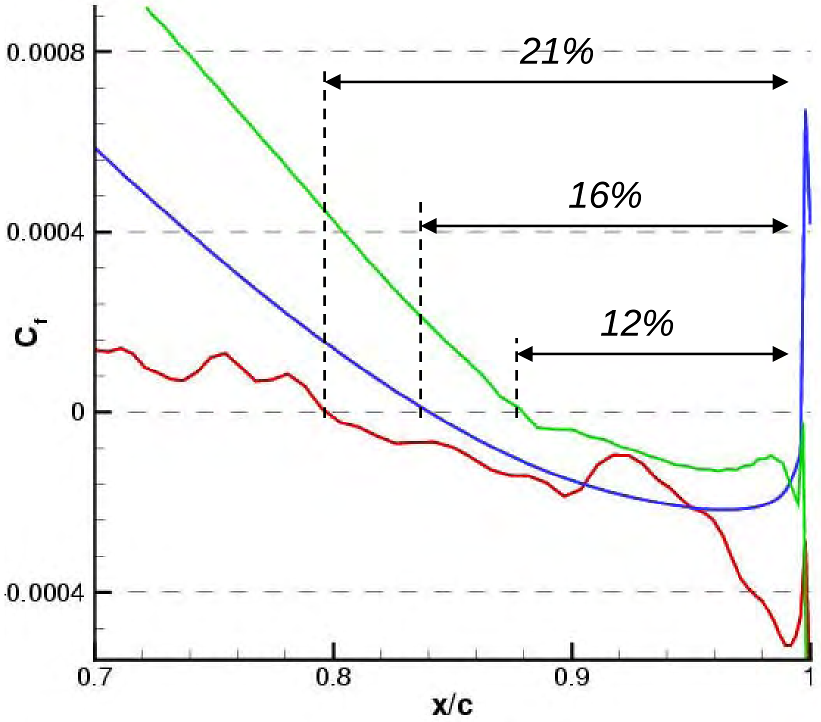
- Increase of the upstream boundary layer thickness,
- then the turbulent boundary layer is thicker on the whole profile,

Zonal RANS/LES results

Skin friction distribution



leading edge



trailing edge

	Experiment	LES	RANS/LES	RANS
Lift	**1.416**	**1.336**	**1.429**	**1.475**
Drag	**0.029**	**0.039**	**0.033**	**0.027**

- Increase of the turbulent separation at the trailing edge
- Lower value of lift coefficient and greater value of drag

CONCLUSION:

- LES: - Grid sensitivity
  - Analysis of the instability mechanism numerically observed in the LSB
- RANS/LES: - Improvement of the RANS solution thanks to a LES domain located in the transitional zone

FOLLOW ON ACTIVITIES:

- LES: - Refine M2 in order to see if the grid sensitivity reduces
- RANS/LES: - Influence of the turbulence model in the RANS domain
  - Simulation for a stalled configuration
- RANS: - Improvement of the transition and intermittence models