High Performance Computing for airfoil noise: present and future

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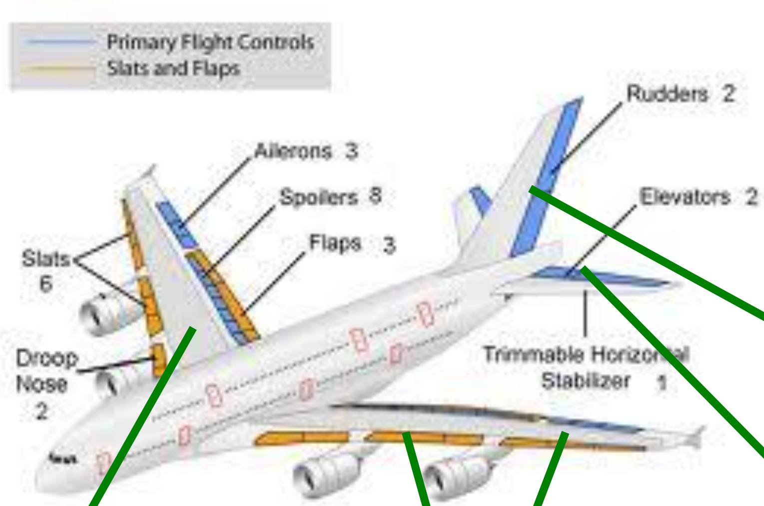
UNIVERSITÉ DE SHERBROOKE

September 18th 2013

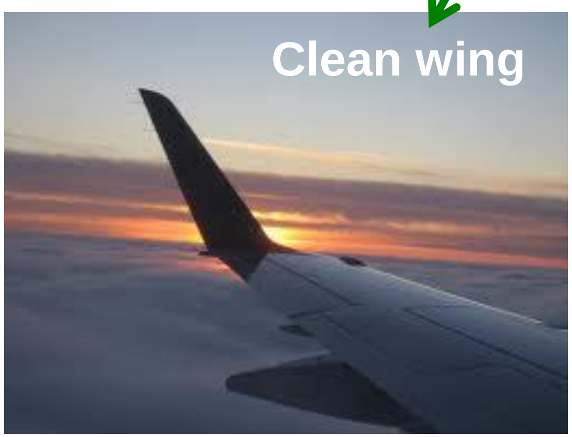
Overall Background -1

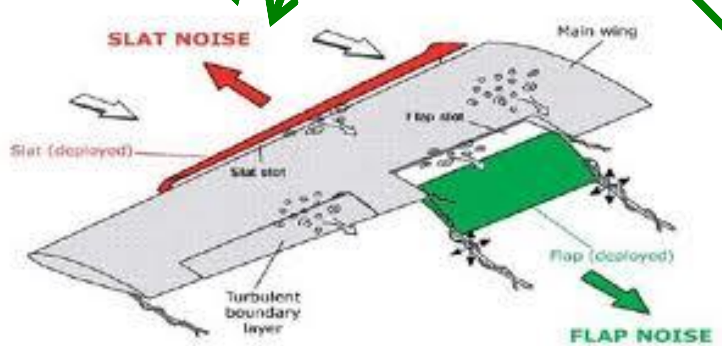
Airfoil noise is the canonical case of wall-bounded flows



All lifting surfaces on an airplane

$Re_c \sim 10^6$; $M \sim 0.3\text{-}0.8$





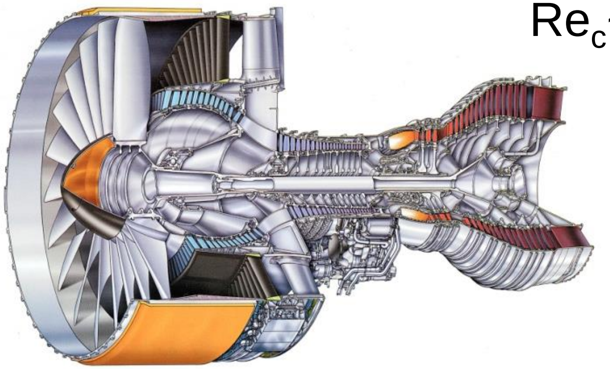
High Lift devices

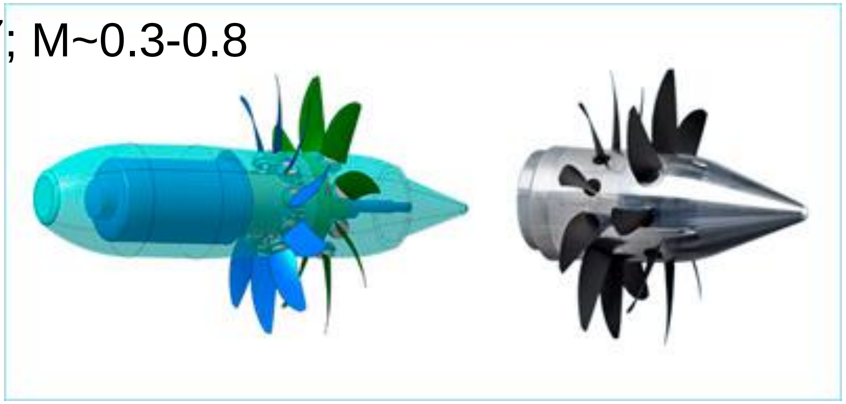
Tail & empennage

Overall Background -2

Propulsion systems

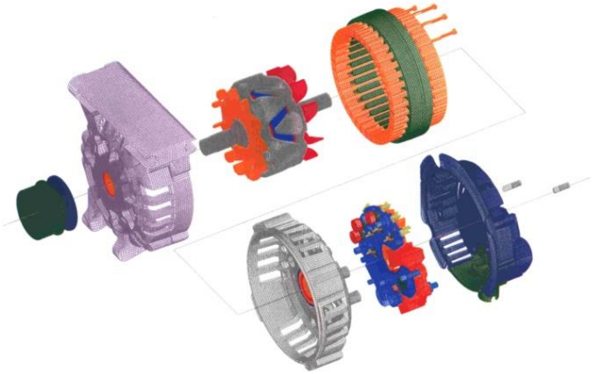
Re_c~10^6-10^7; M~0.3-0.8

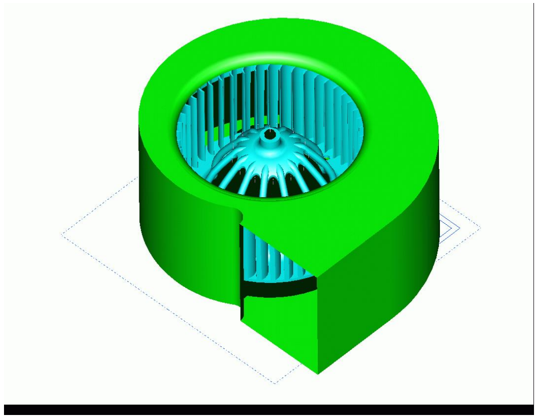




Ventilation systems

Re_c~10^4-10^5; M~0.05



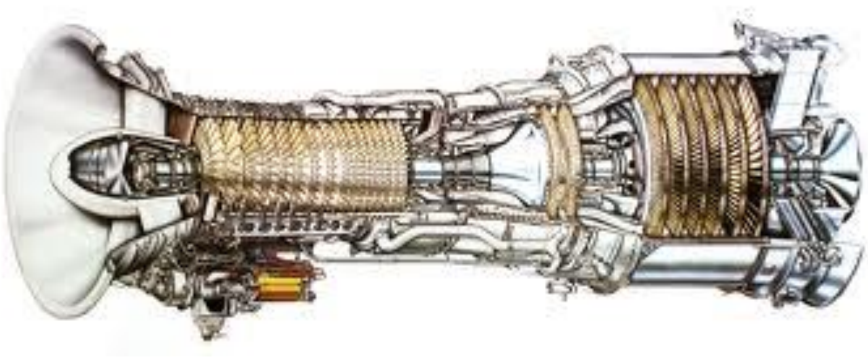


➪Noise annoyances in daily life

Overall Background -3

Power generation noise

$Re_c \sim 10^6 - 10^7$; $M \sim 0.3 - 0.8$

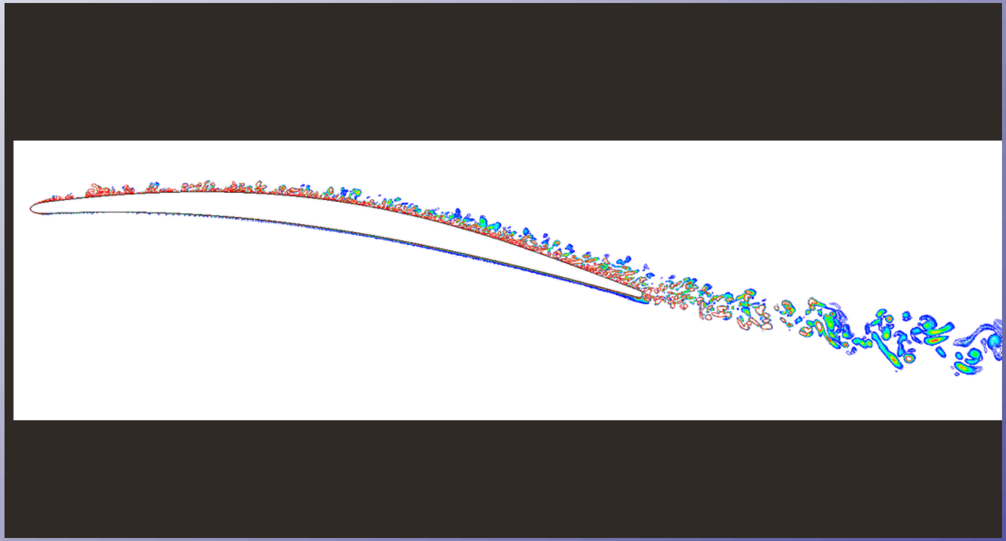


Airframe noise (landing gear)

$Re_c \sim 10^6$; $M \sim 0.15 - 0.2$

Airfoil Canonical Cases

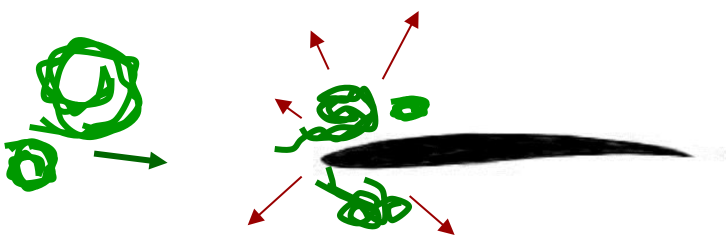
Msc: L. Corriveau
PhD, Post-doc: J. Winkler
PhD, Post-doc: J. Christophe
PhD: J.C. Giret
Post-doc: M. Sanjose



Airfoil Noise Mechanisms

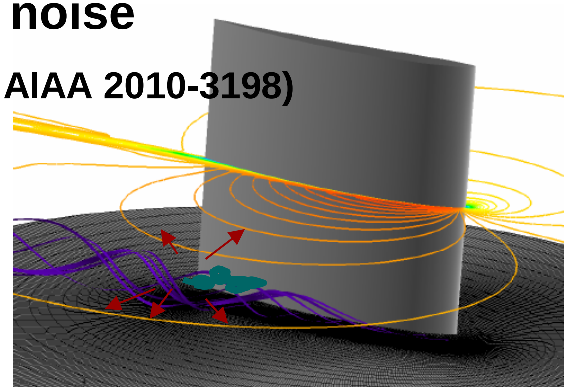
On an airfoil, wall-pressure and loading fluctuations induced by a turbulent vortical field can be produced by several mechanisms :

Turbulence-interaction noise

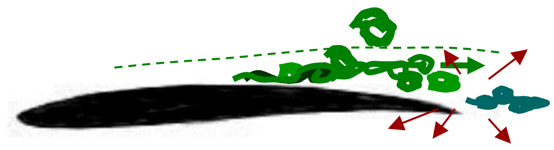


Tip noise

(Boudet et al AIAA 2010-3198)



Trailing-edge noise

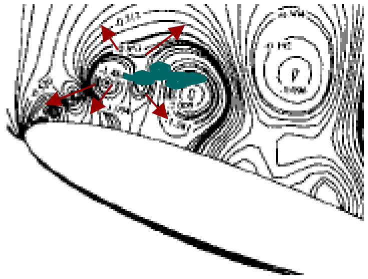


Vortex shedding noise

(AIAA 2010-3804, 2011-2933, AIAA2012-2112)

Stall noise

(AIAA 2009-3198)

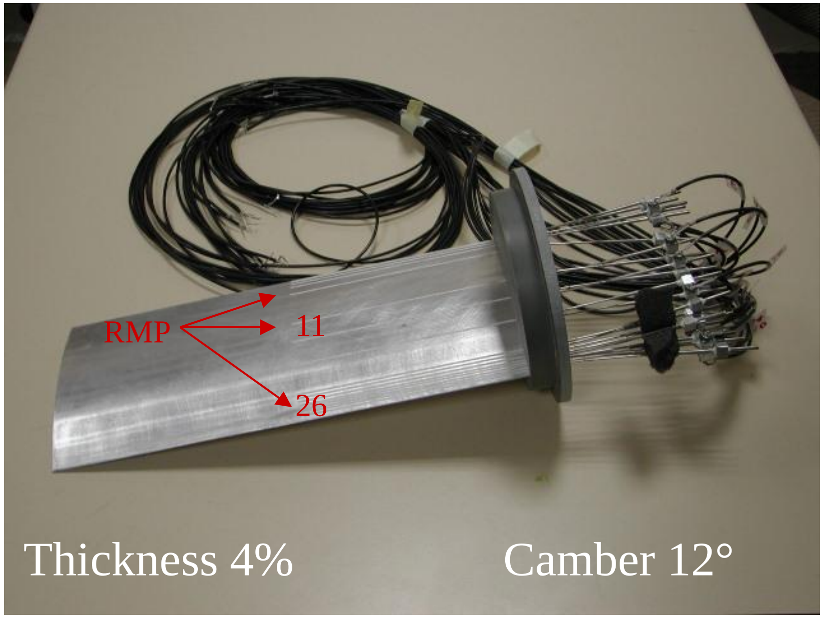


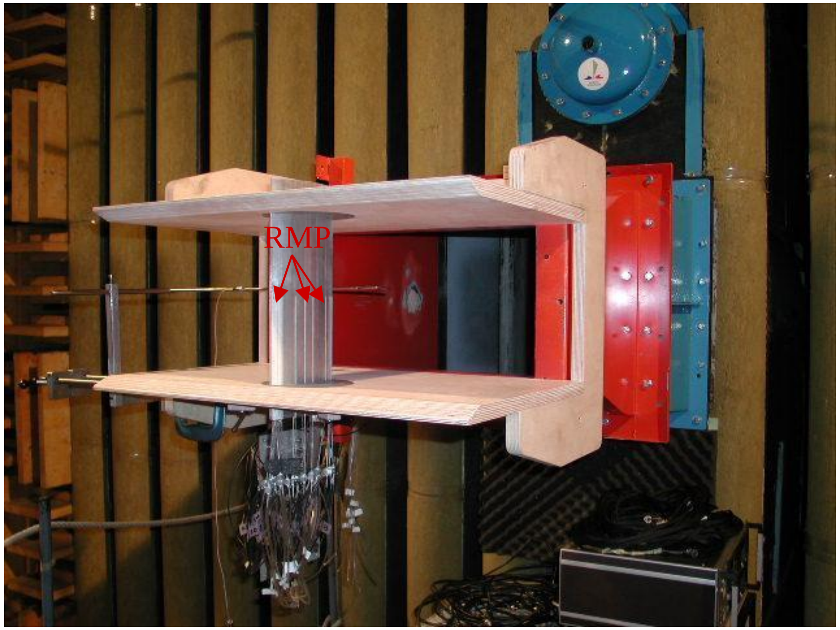
Airfoil Noise Validation

Open-Jet Aeroacoustic Experiment in ECL Large Wind Tunnel

Airfoil chord length ~*10 cm*

$$16\ m/s \le U_0 \le 40\ m/s$$





Valeo CD and NACA12 airfoils,
Flat Plate, V2 and V3 airfoils

Nozzle exit section *50 cm x 25 cm*

CAA Methods

- Hybrid methods:
  - ➢ Detailed geometry and high-fidelity flow field (unsteady CFD).
  - ➢ Mostly incompressible simulations at low speed
  - ➢ Noise prediction in a second step resorting to an Acoustic Analogy.

- Direct methods:
  - ➢ Detailed geometry and high-fidelity flow field (unsteady CFD).
  - ➢ Compressible flow simulations only.
  - ➢ Mostly near-field simulations.

Hybrid Acoustic Prediction

- Solution to Ffowcs-Williams and Hawkings' analogy (*free space Green's function*) ➔ Curle's analogy for fixed airfoil:

$$c_0^2 \rho'(\vec{x},t) = \frac{1}{4\pi}\frac{\partial^2}{\partial x_i \partial x_j}\int_{V(t)} \left[\frac{T_{ij}}{R|1-M_r|}\right] dV - \frac{1}{4\pi}\frac{\partial}{\partial x_i}\int_{S(t)} \left[\frac{p\, n_i}{R|1-M_r|}\right] dS - \frac{1}{4\pi}\frac{\partial}{\partial t}\int_{S(t)} \left[\frac{\rho_0 V_n}{R|1-M_r|}\right] dS$$

Low Mach number assumption

- Other analogies used here:
  - Amiet's model based on Curle's analogy (*free space Green's function*) with an unsteady airfoil response for a finite chord-length flat plate.
  - Ffowcs-Williams and Hall' model based on Howe's finite chord flat plate Green's function.

Typical Numerical Set-up

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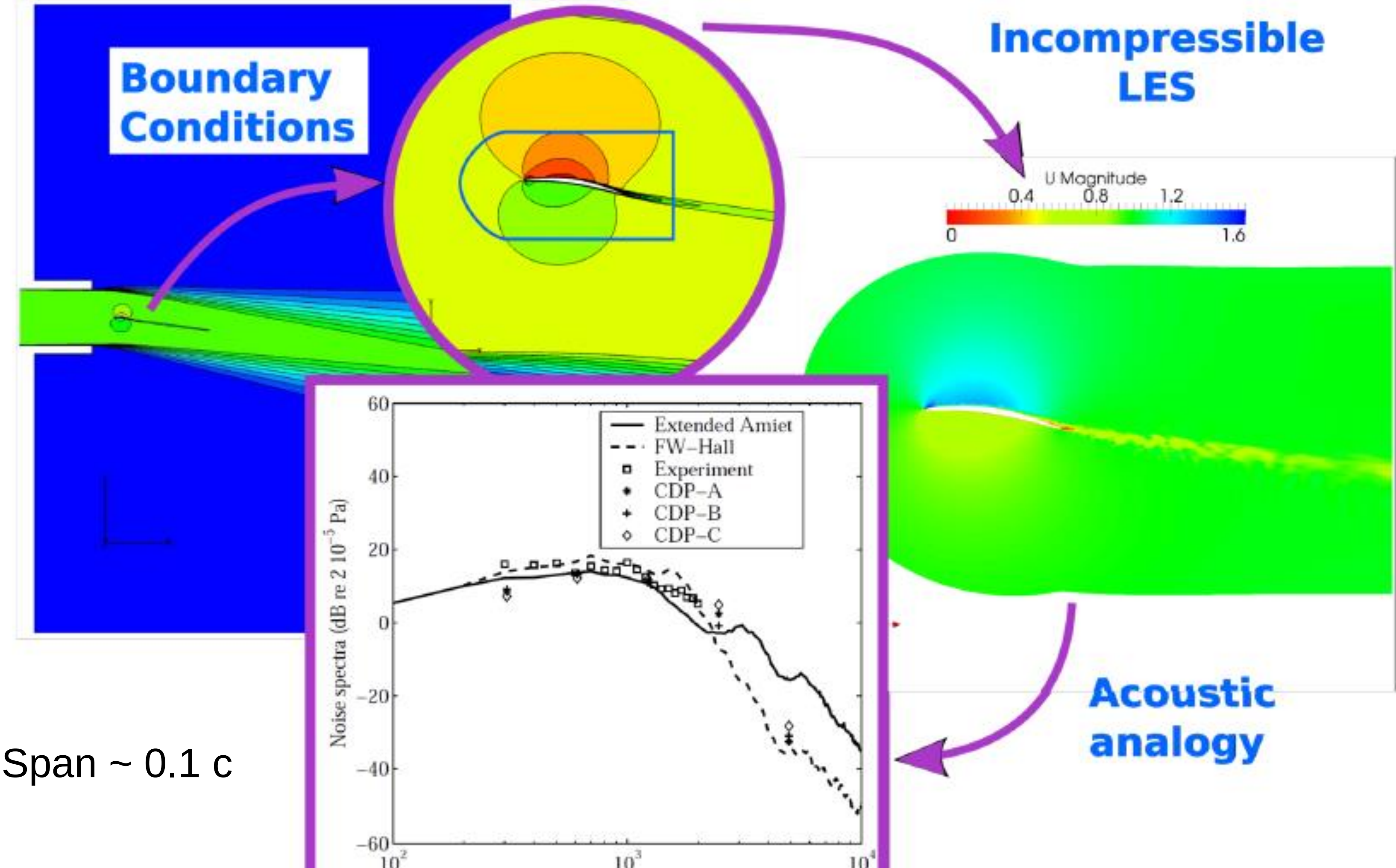
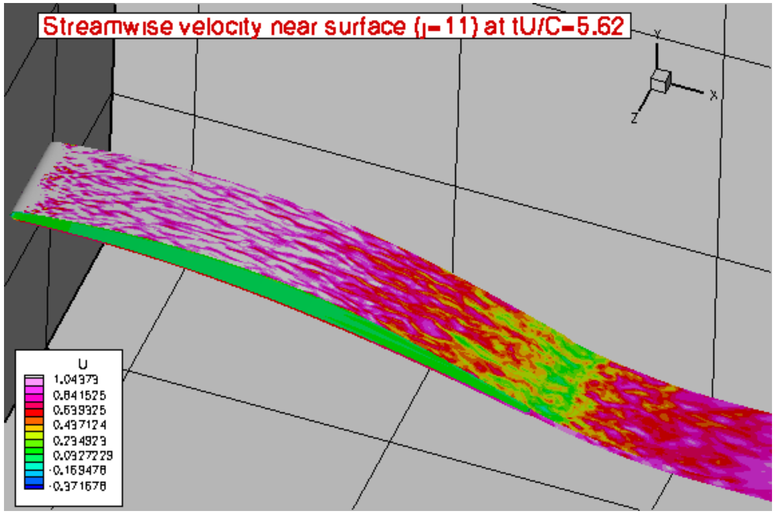


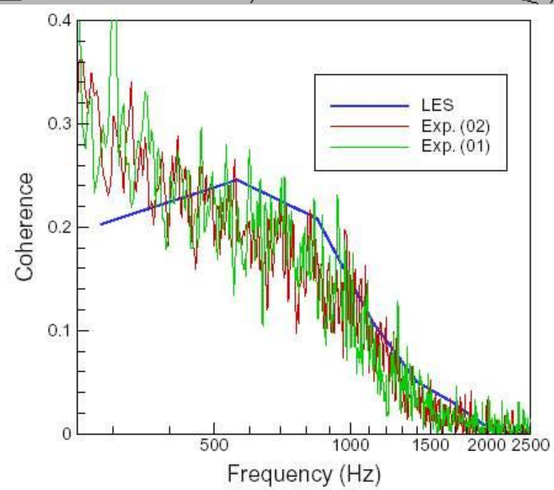
Span ~ 0.1 c

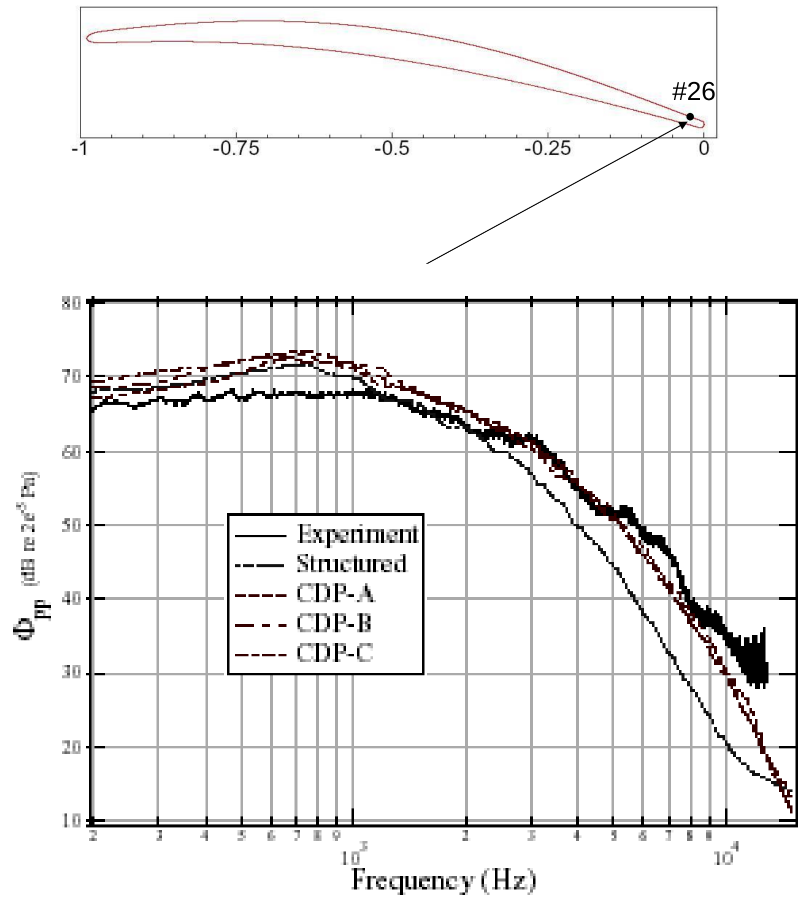
Effect of the jet accounted for on both mean and fluctuating flow fields

First Results on CD airfoil (8º)

Simulation of noise sources: LES on CD airfoil with Stanford (Affiliates 2003)







5 million nodes for a 6 month to a year *scalar* run

IJA 2009

Flow topology on CD airfoil (8º)

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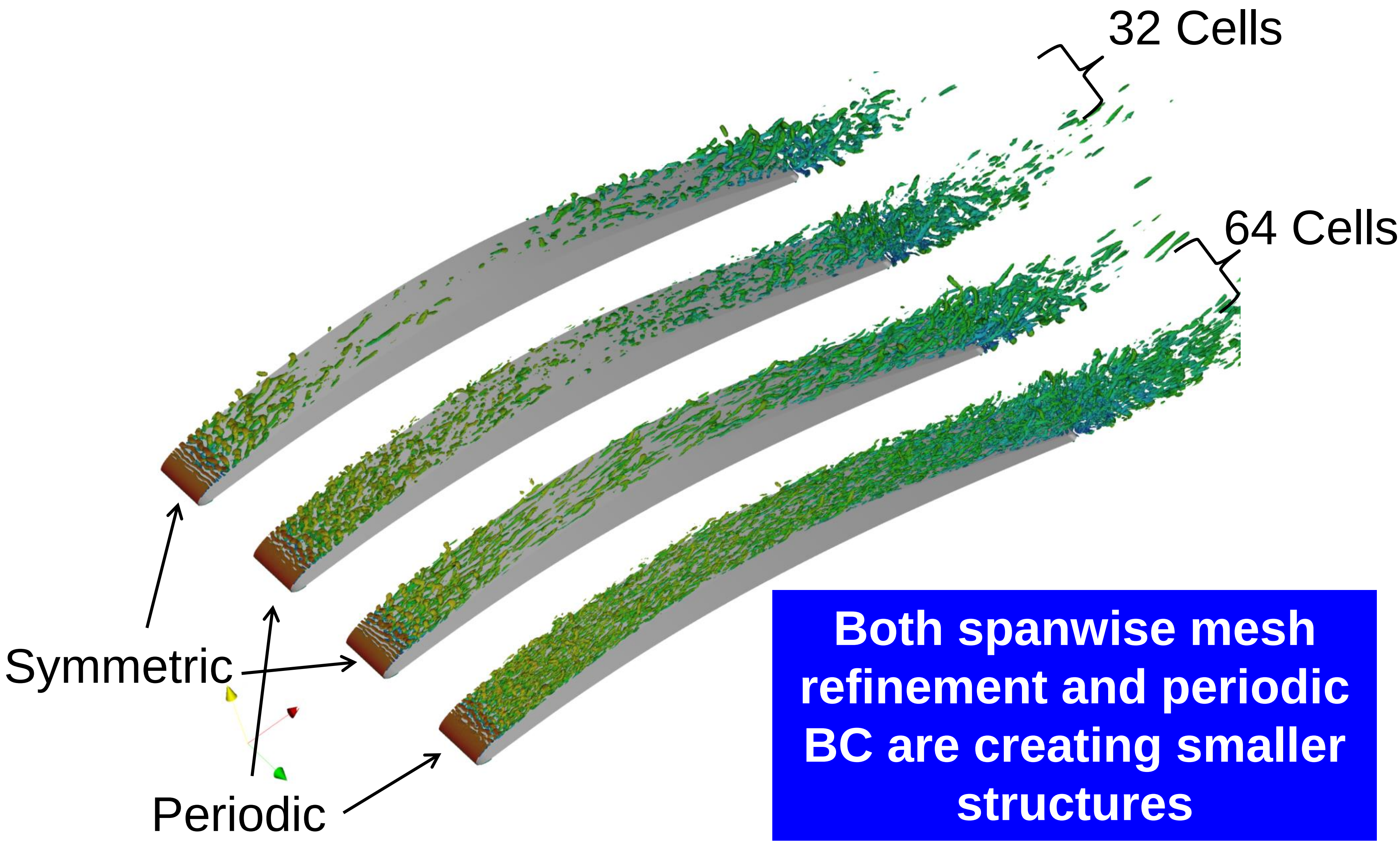

Both spanwise mesh refinement and periodic BC are creating smaller structures

3-12 million nodes for a 2-3 month parallel run (32-64 procs)

AIAA 2009-3196

LES CD airfoil at other incidences -1

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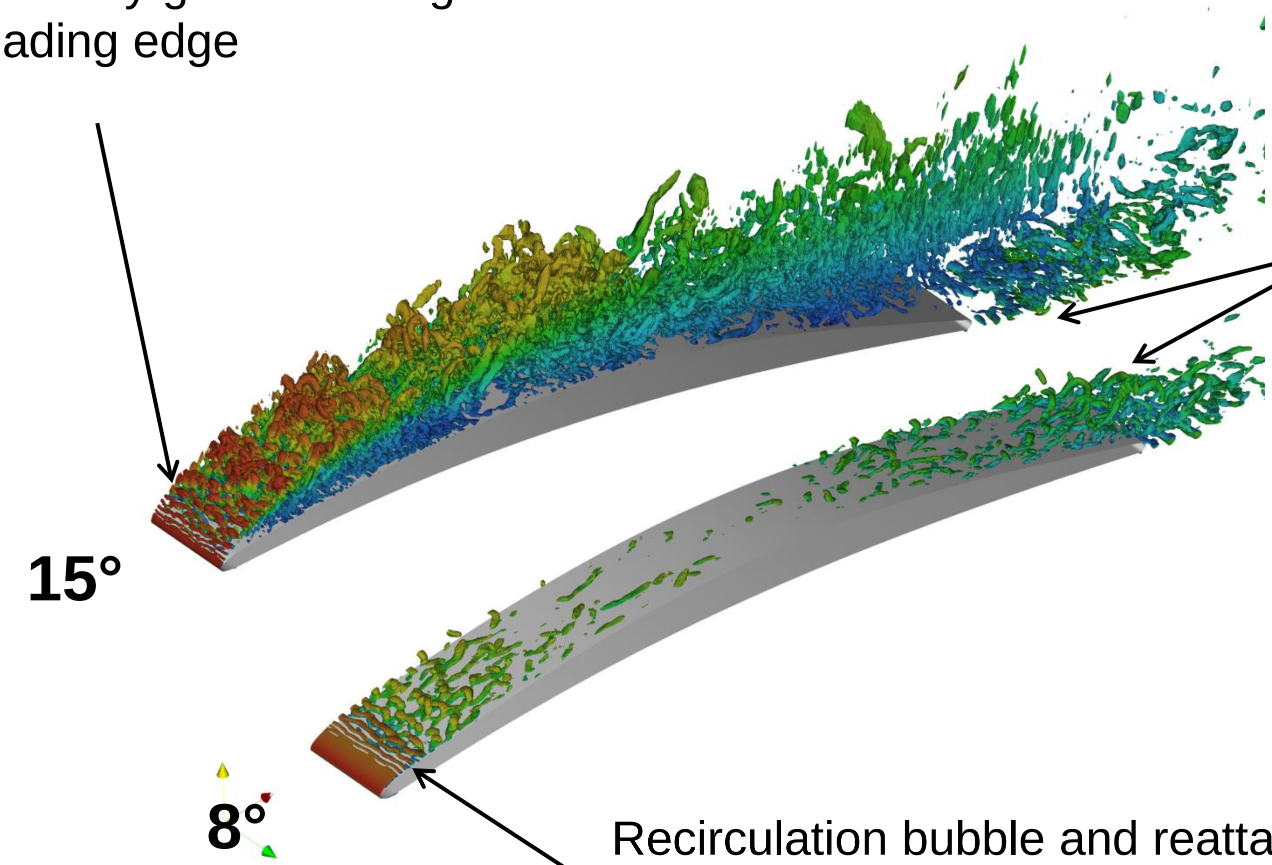
Strong vorticity generation right at the leading edge



Weak vortex shedding

Recirculation bubble and reattachment triggering turbulent boundary layer

Detailed flow topology nicely captured at various flow regimes

AIAA 2009-3196

LES CD airfoil at other incidences -2

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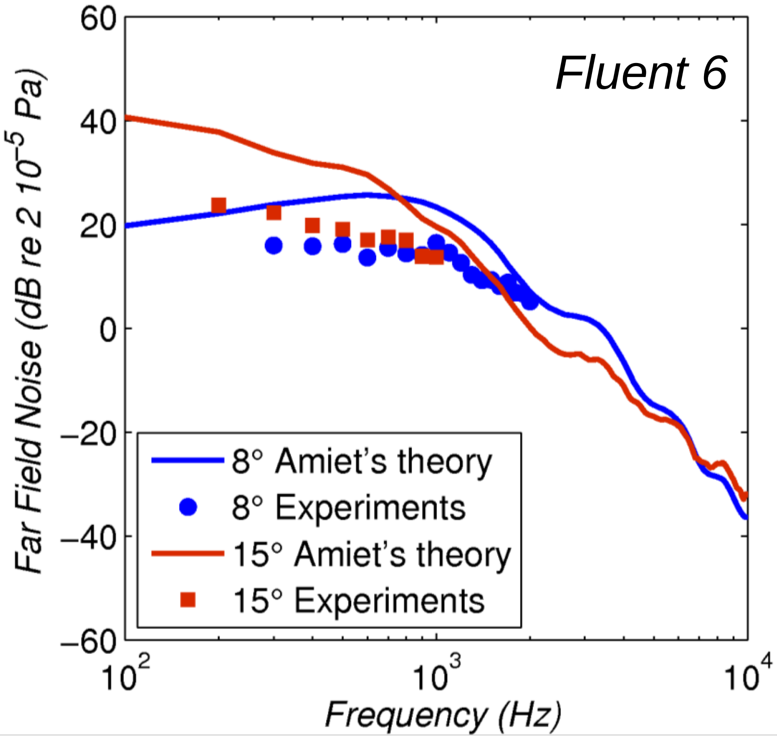
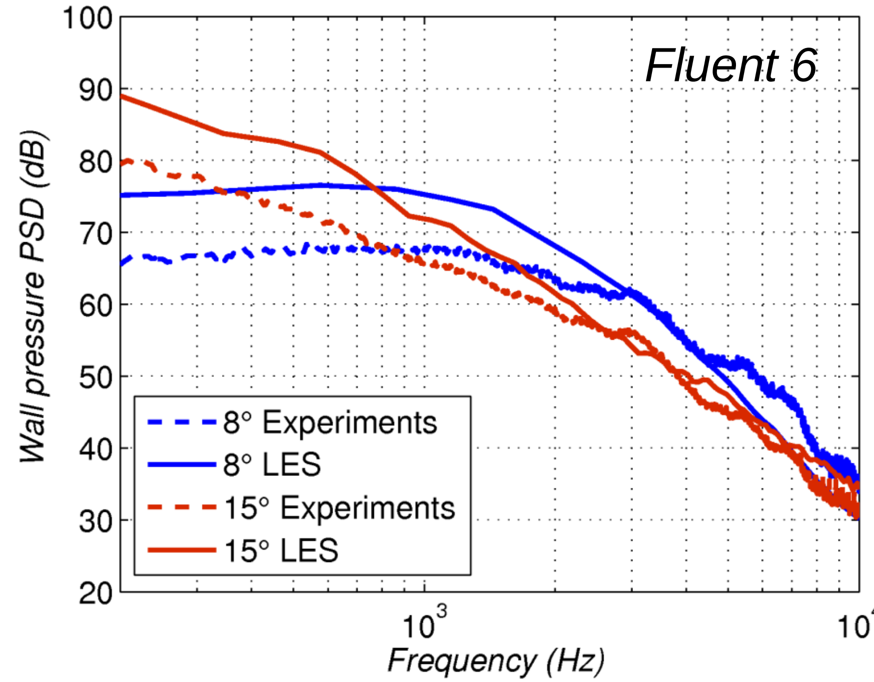
Far-field acoustic pressure



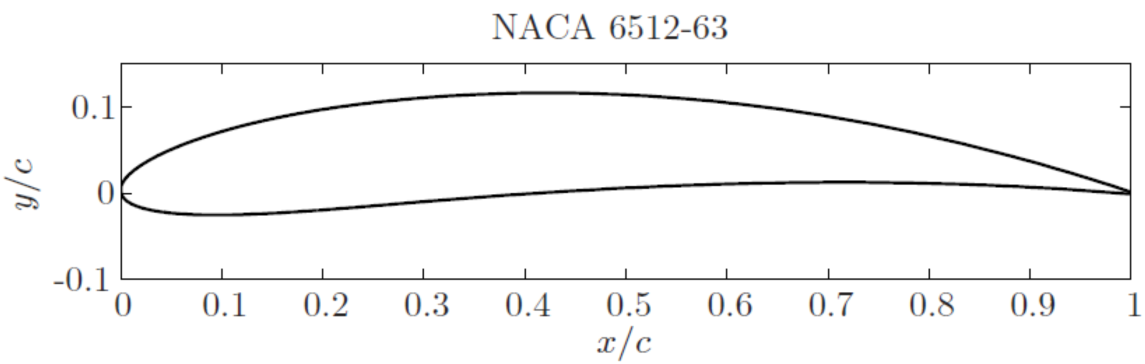
Wall-pressure fluctuations

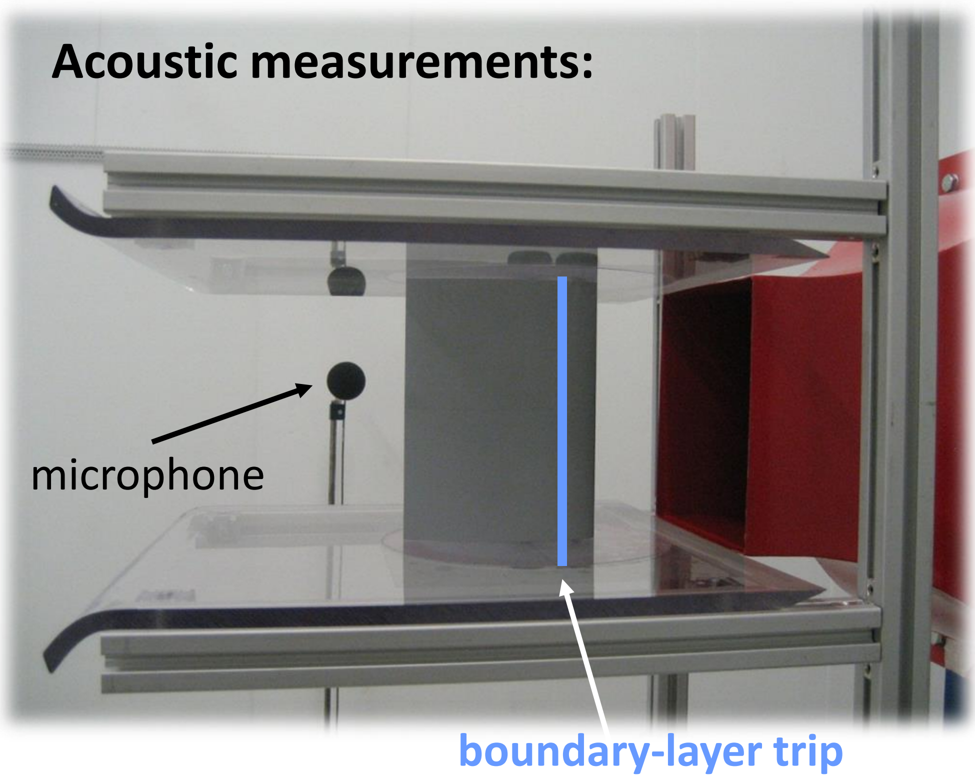


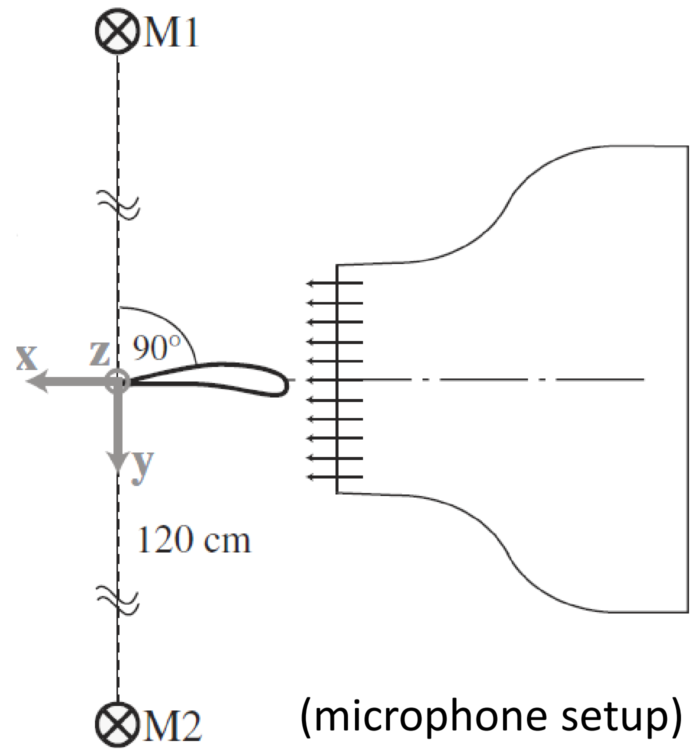
Good overall agreement for all simulations
Same trend as experiment for all a.o.a

AIAA 2009-3196

Siegen experimental set-up







(microphone setup)

LES NACA6512 airfoil with tripping

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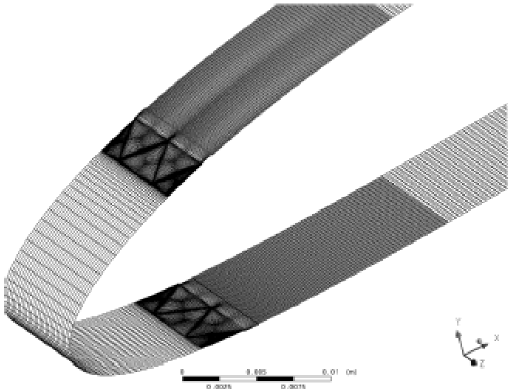

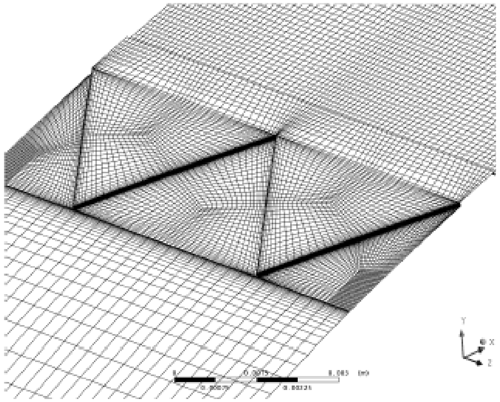

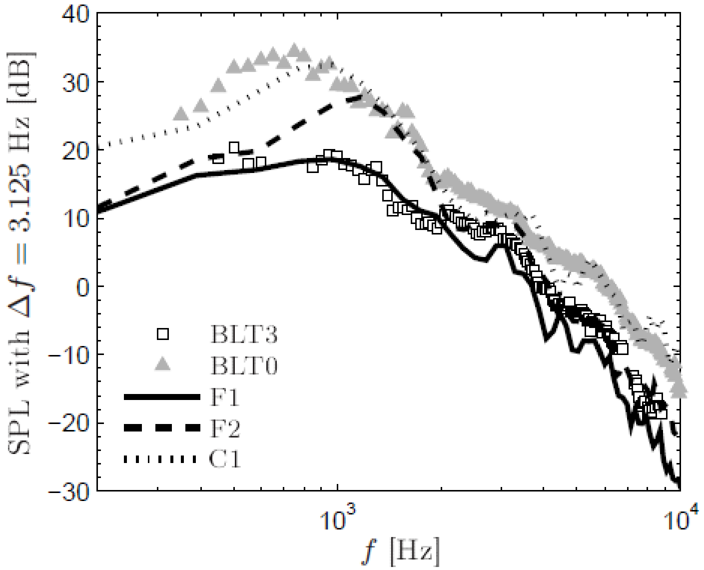

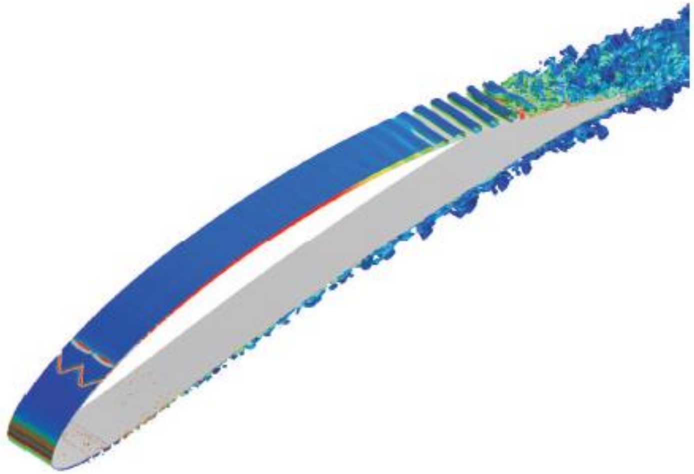

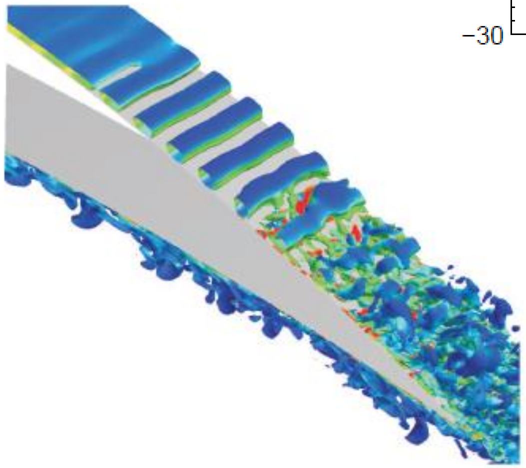

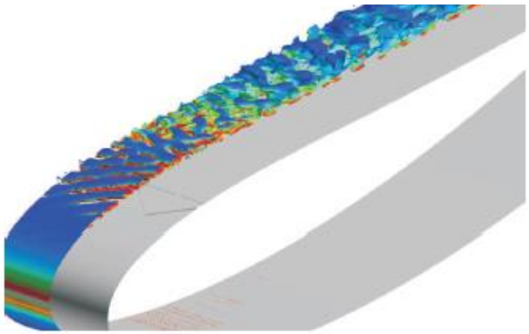

Careful selection of numerical parameters for transition
Effect of tripping thickness correctly captured

AIAA 2009-3197

LES NACA6512 airfoil with blowing

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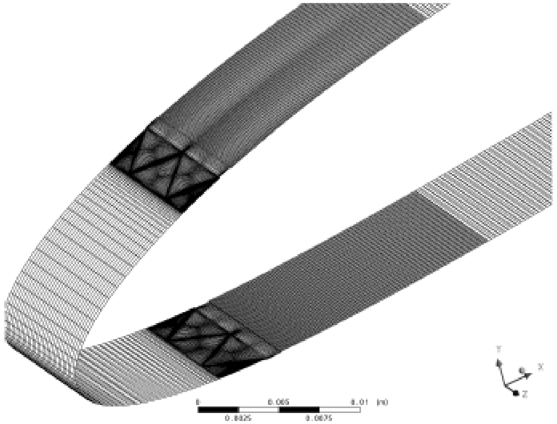
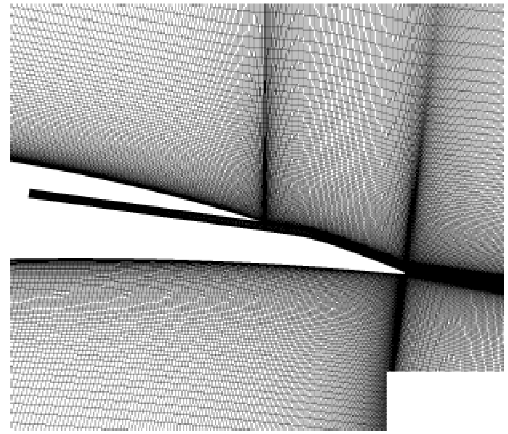
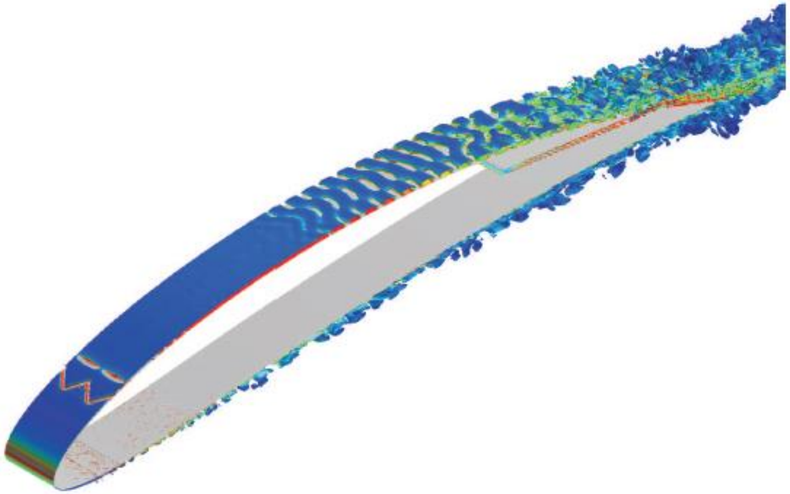
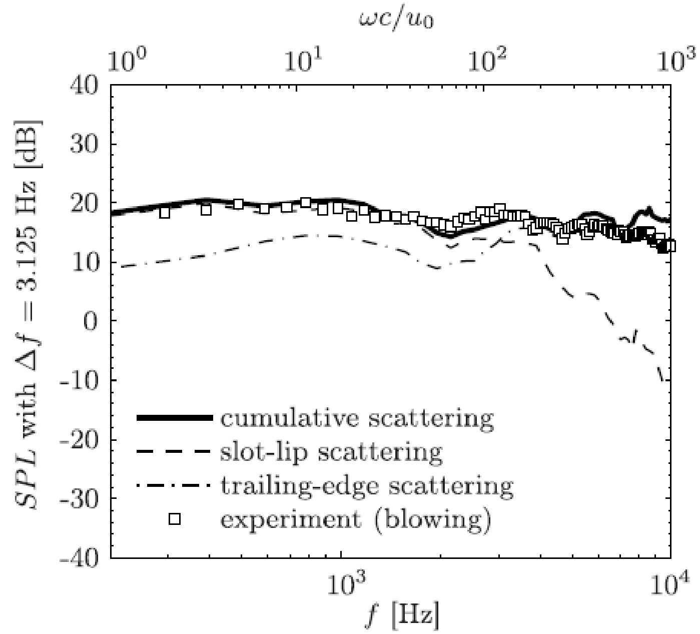


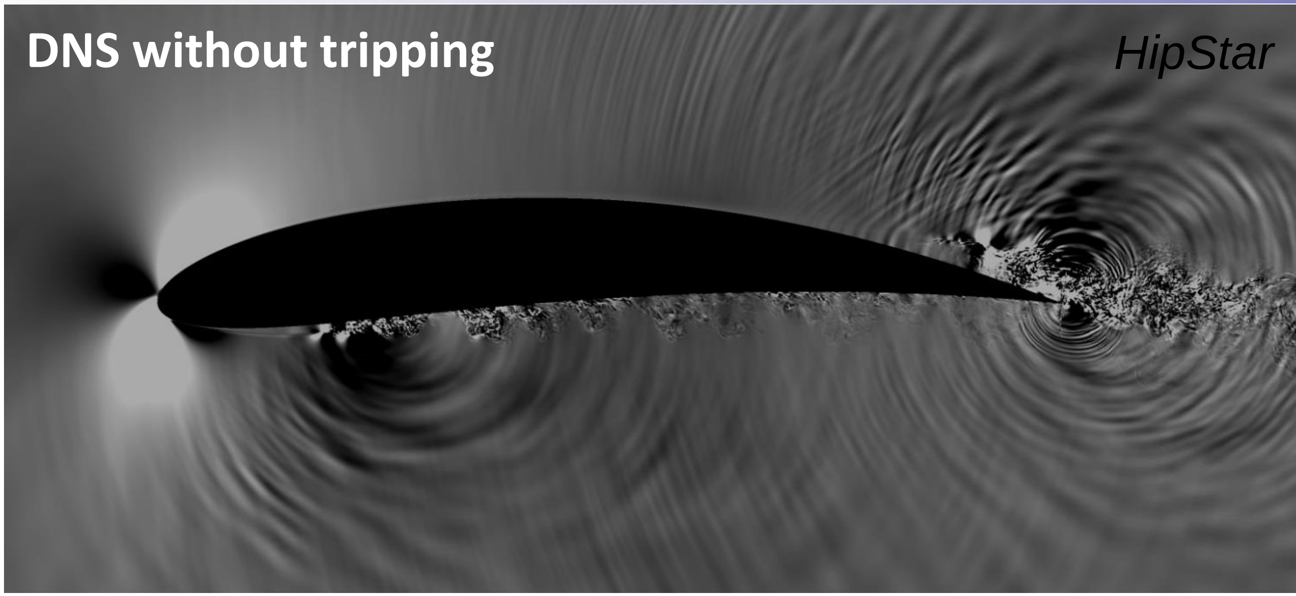


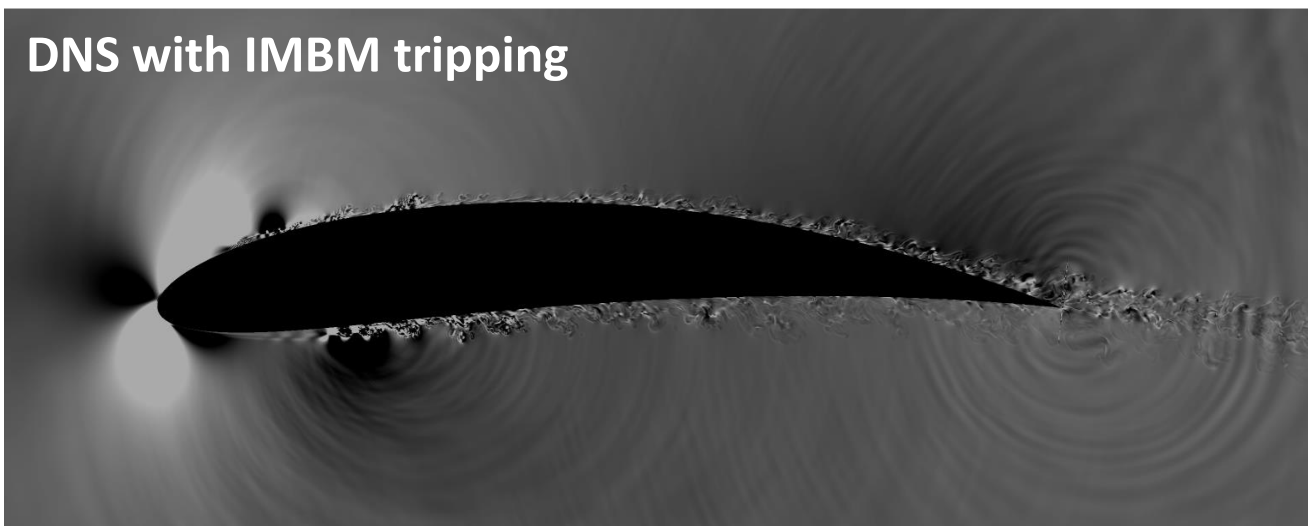




Good overall prediction of acoustic pressure
Trailing edge noise responsible for added noise at high f

Compressible DNS Results (Re_c~10^5)

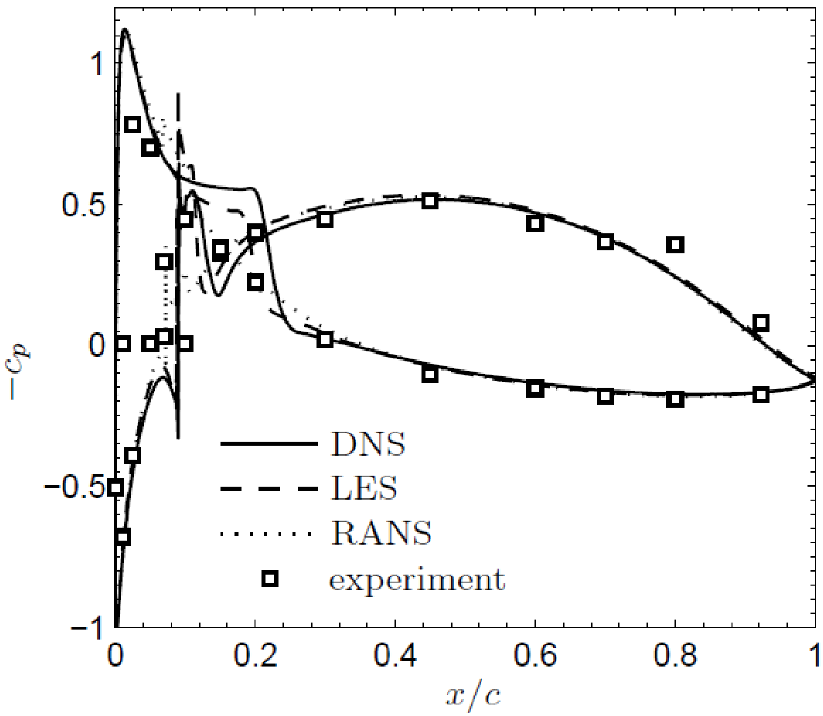




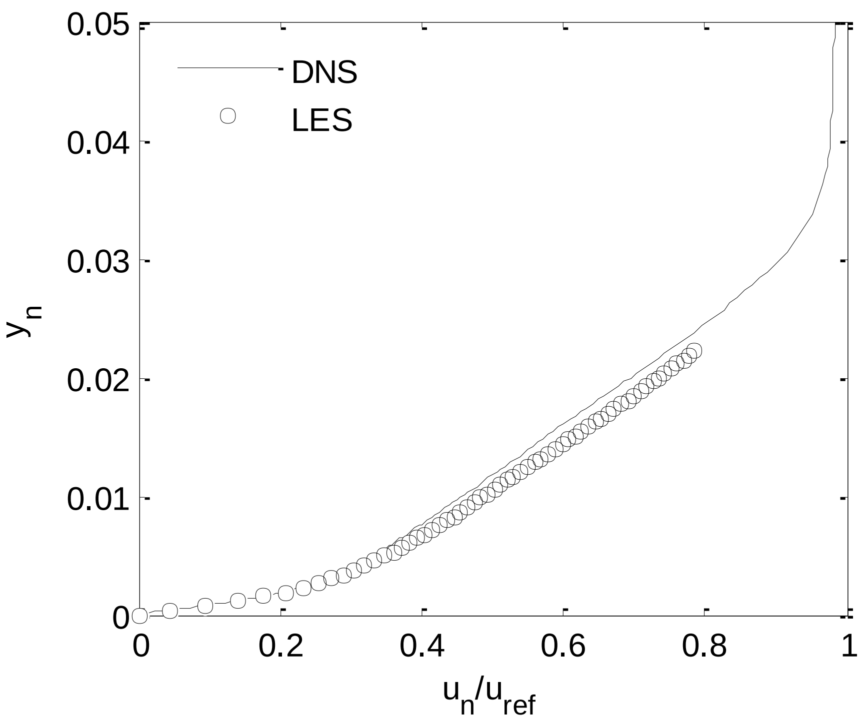
261 millions of nodes for a week parallel run (4000-6000 procs) *AIAA 2012-2059*

NACA6512 DNS mean flow (Re_c~10^5)

Wall pressure coefficient



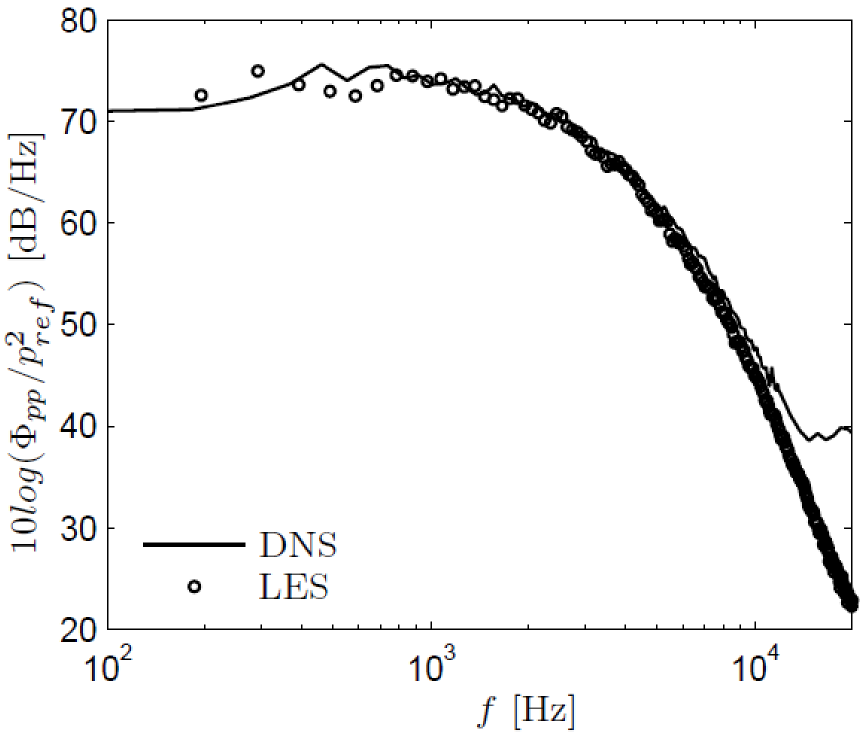
BL velocity profile near TE



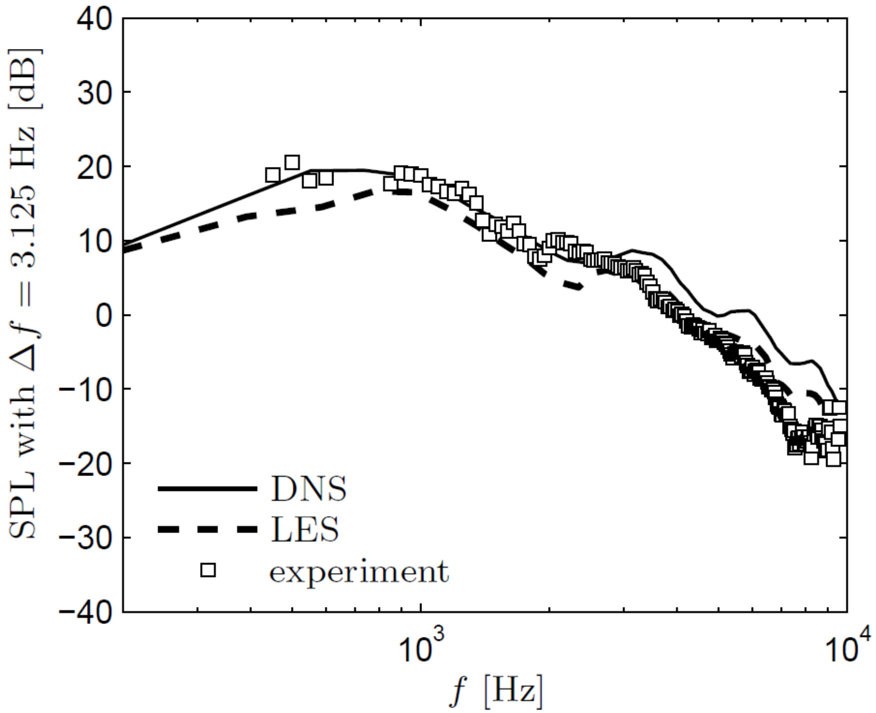
Very similar wall pressure loading
Transition occurs almost at same position
Very similar velocity profile near the trailing edge

NACA6512 DNS noise predictions

Wall-pressure fluctuations



Far-field acoustic pressure



Very similar wall pressure fluctuation near TE
Very similar trailing-edge noise based on Amiet's acoustic analogy

Compressible DNS Results (Re_c~10^5)

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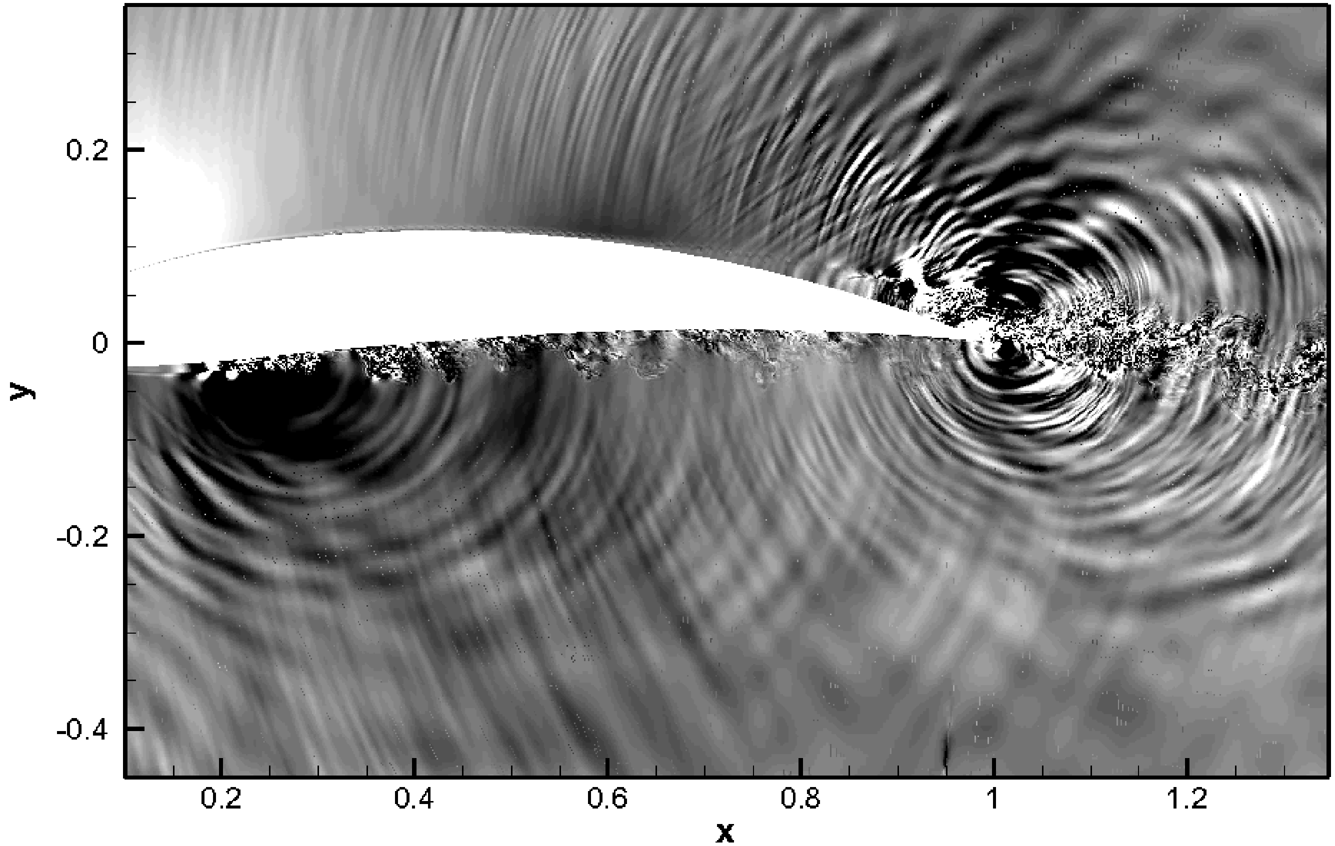
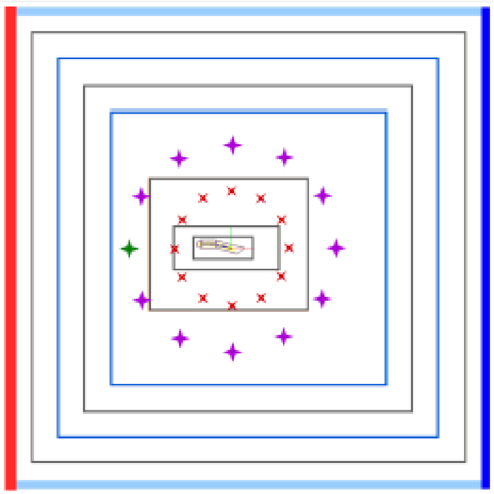


Very complex dilatation field w/o tripping
Additional noise source on PS reattachment point

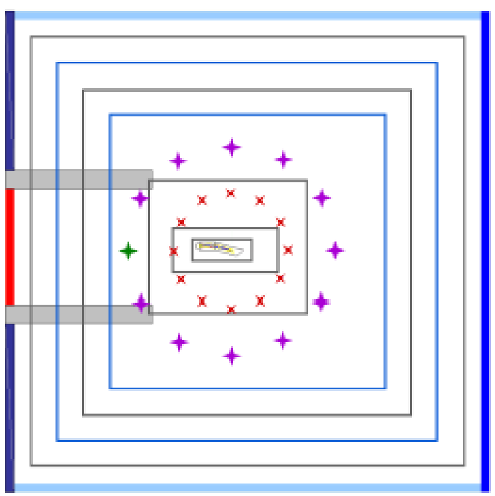
Full set-up LBM compressible DNS

Université de Sherbrooke

Free-field



Nozzle



Lattice-Boltzmann Method

- Powerflow 4.3a
- Discrete Lattice-Boltzmann equation
- Compressible (low Mach number formulation)
- DNS resolution achieved in the first 3 VR
- 2D setups: 28 million cells
- 3D setup (nozzle): 12% *C* span length, 640 million cells

Case	Phys. Time	CPU Time
2D set-ups	0.4 s	2,095 hrs
3D set-up	0.1 s	87,400 hrs

processors Intel Xeon X5560 @ 2.80GHz

AIAA 2011-2716

2D LBM Dilation fields ($Re_c \sim 10^5$)

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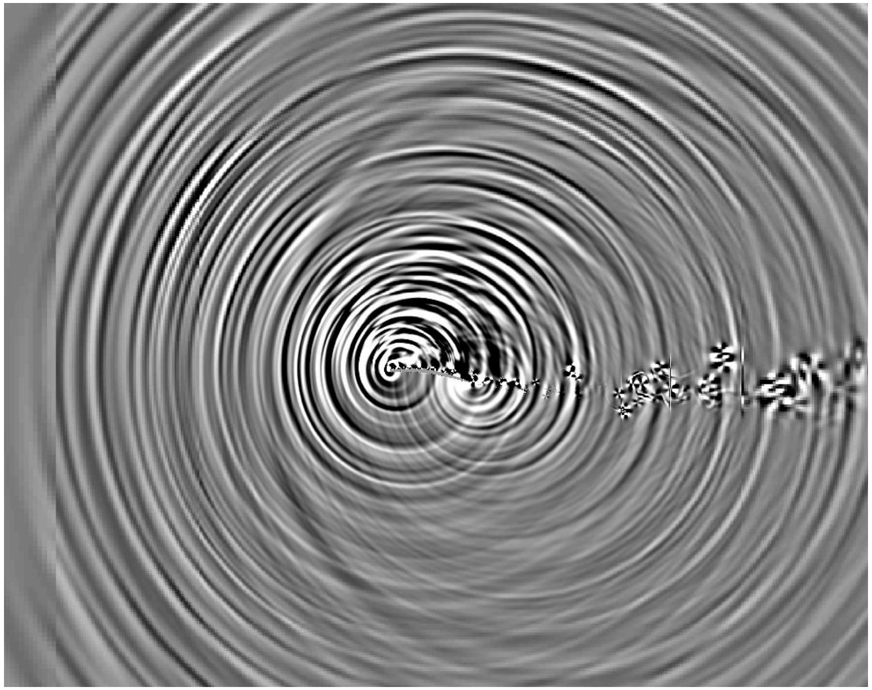
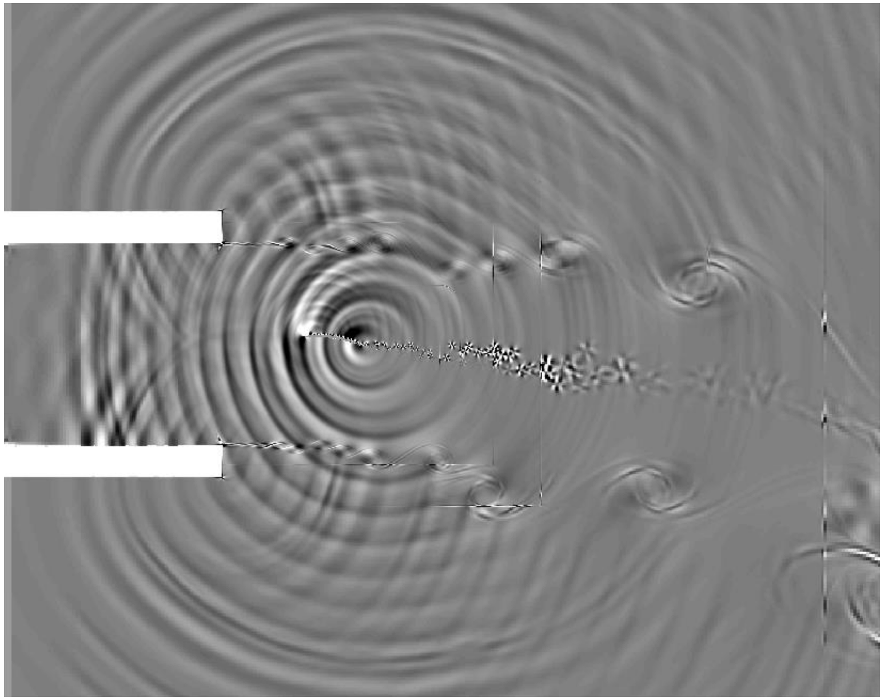
Free Field



Nozzle



Free-field similar to low Re_c DNS
Cardioid shape of main trailing-edge noise
Diffraction effect of the nozzle lips captured
Weaker noise source at the bubble reattachment point

3D LBM Dilation & velocity fields ($Re_c \sim 10^5$)

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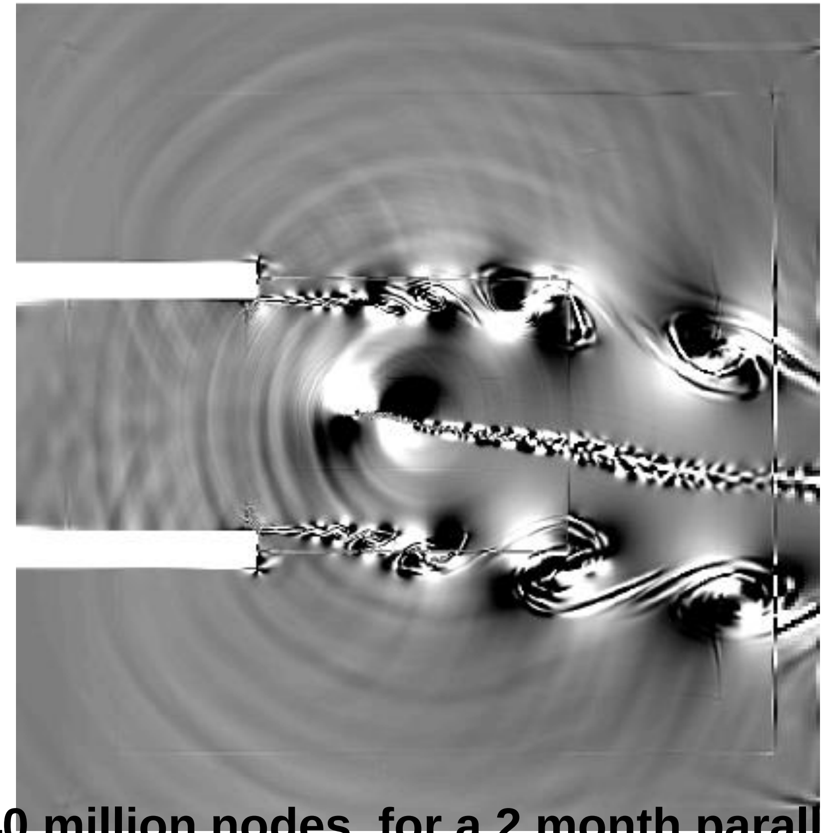
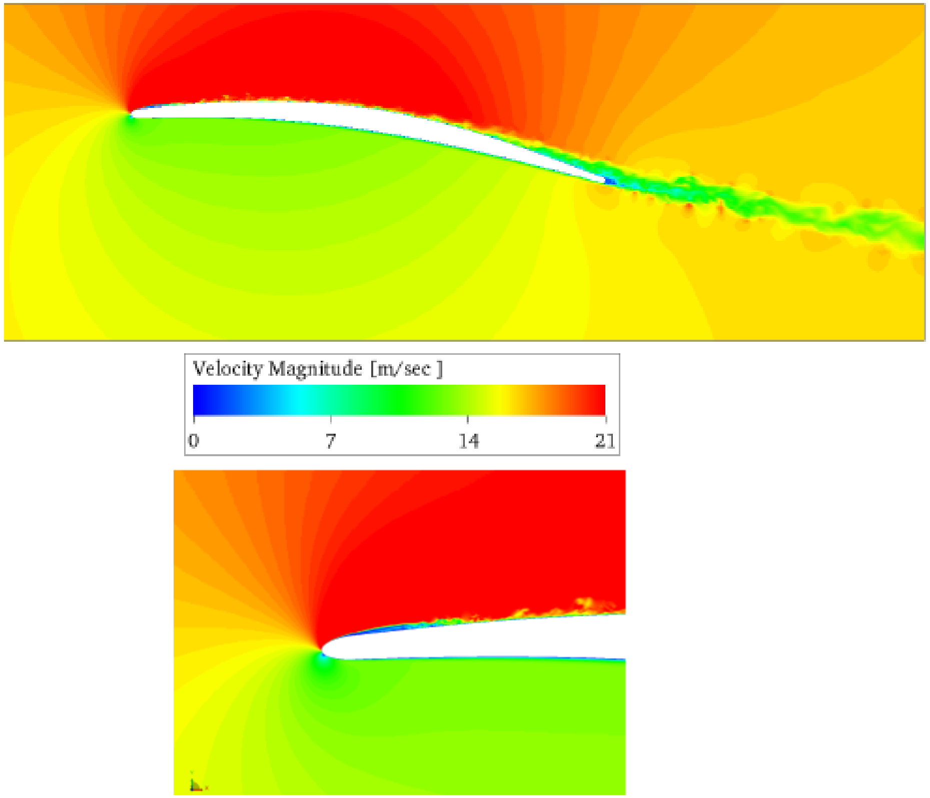


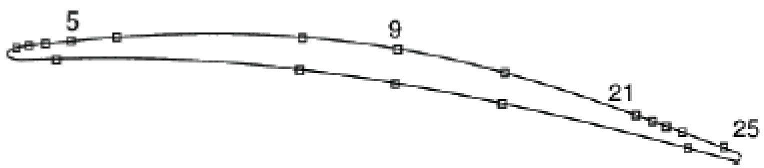


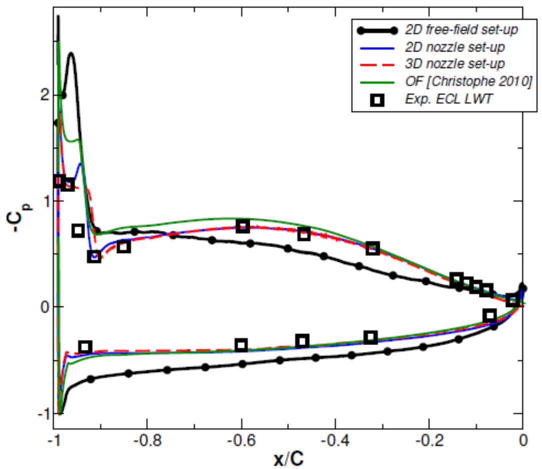
640 million nodes for a 2 month parallel run (528 procs)

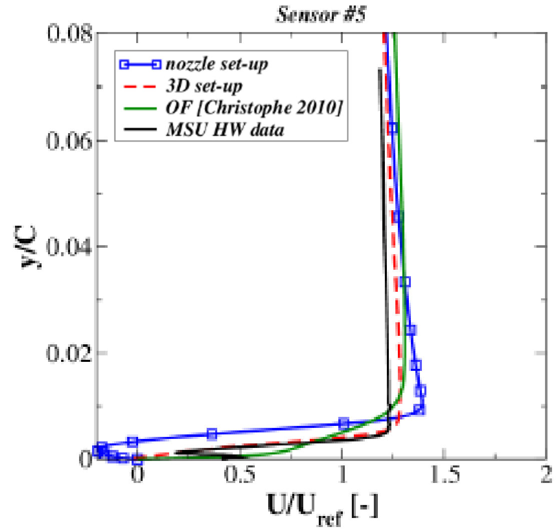
Much smaller flow structures on airfoil and wake
Strong vortex pairing in the jet shear layers
Dominant trailing edge mechanism
Almost no noise source at the bubble reattachment

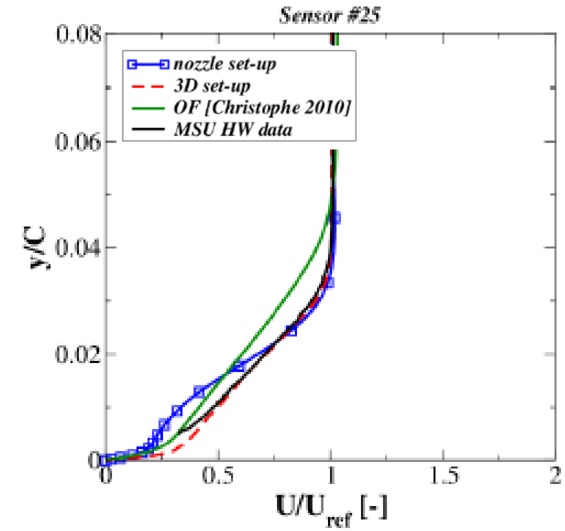
All LBM mean flow field ($Re_c \sim 10^5$)

case	δ^*
2D free-field	7 mm
2D nozzle	2 mm
3D nozzle	1.7 mm
MSU hot-wire	1.8 mm



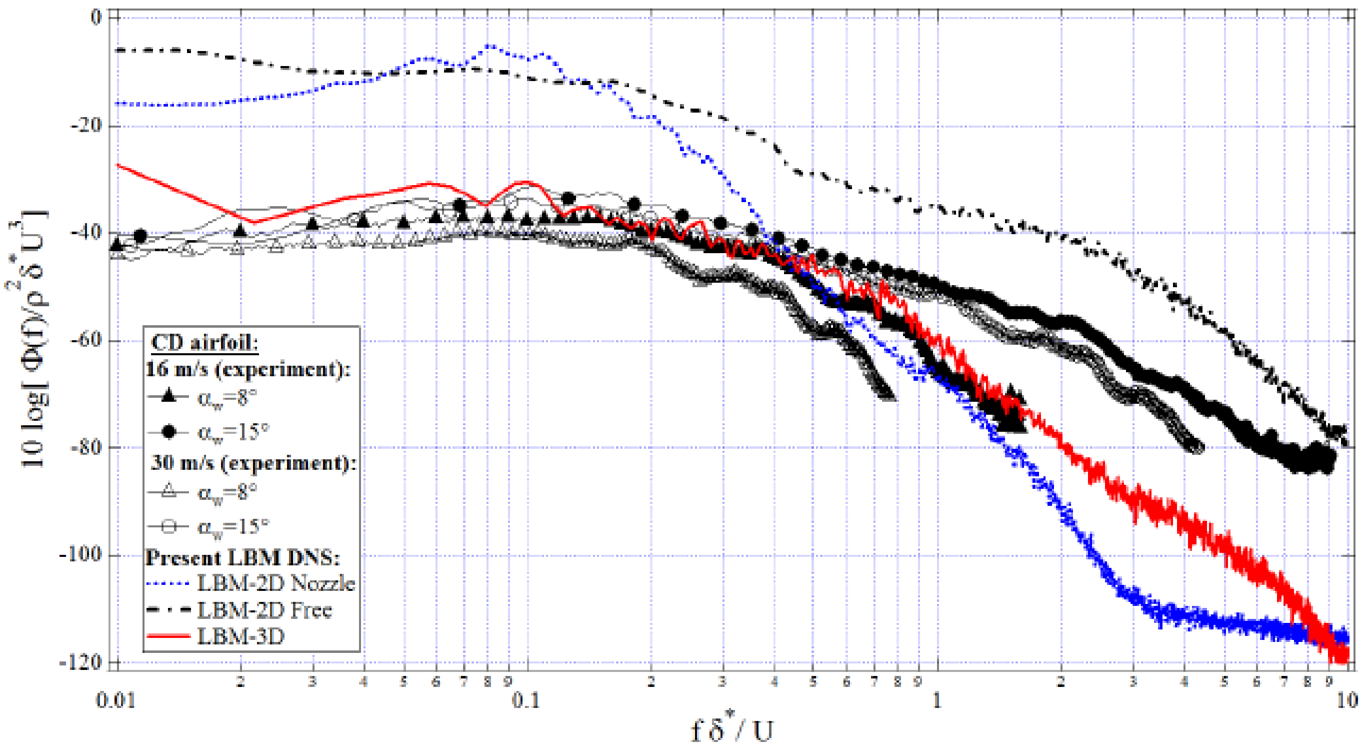






Similar load for 2D and 3D LBM with nozzle
Very good agreement with wall pressure sensors
Excellent agreement of 3D LBM with HW
Only the wall-shear stress is over-estimated

3D LBM Wall pressure spectra (TE)

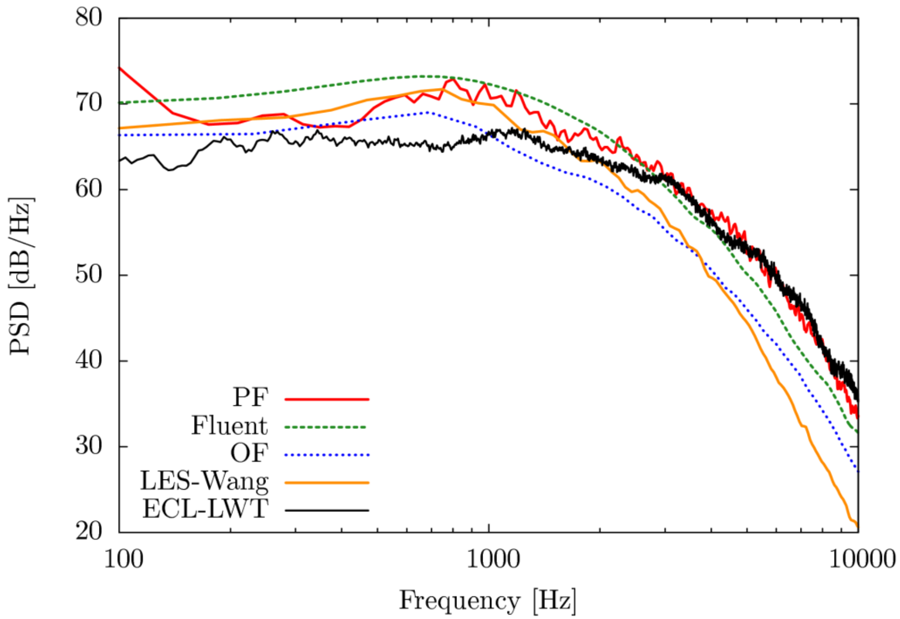


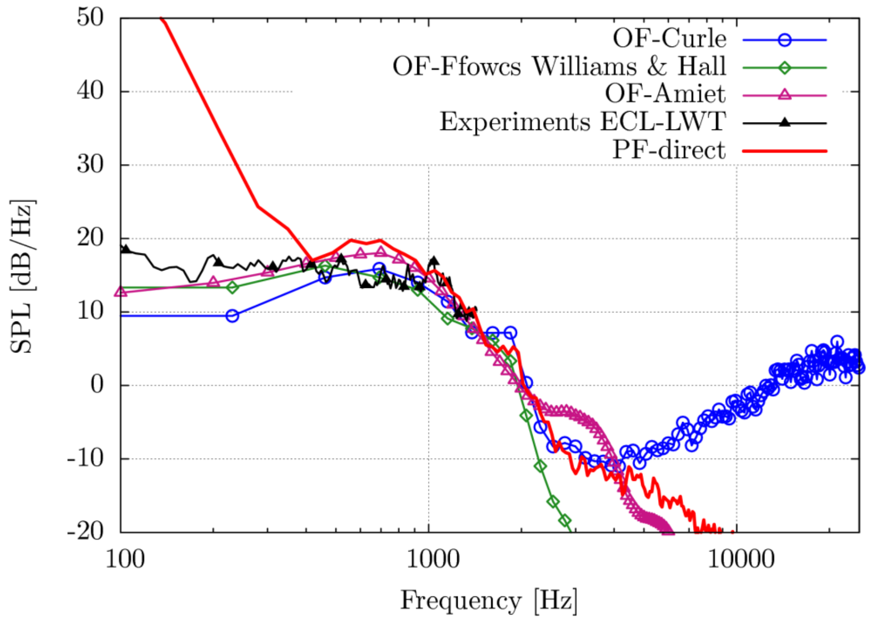
Overestimation in 2D due to too large vortical structures
Free-field: characteristic spectra of a detached flow (15º)
Excellent agreement of the 3D set-up

Source/Noise Predictions

Wall-pressure fluctuations

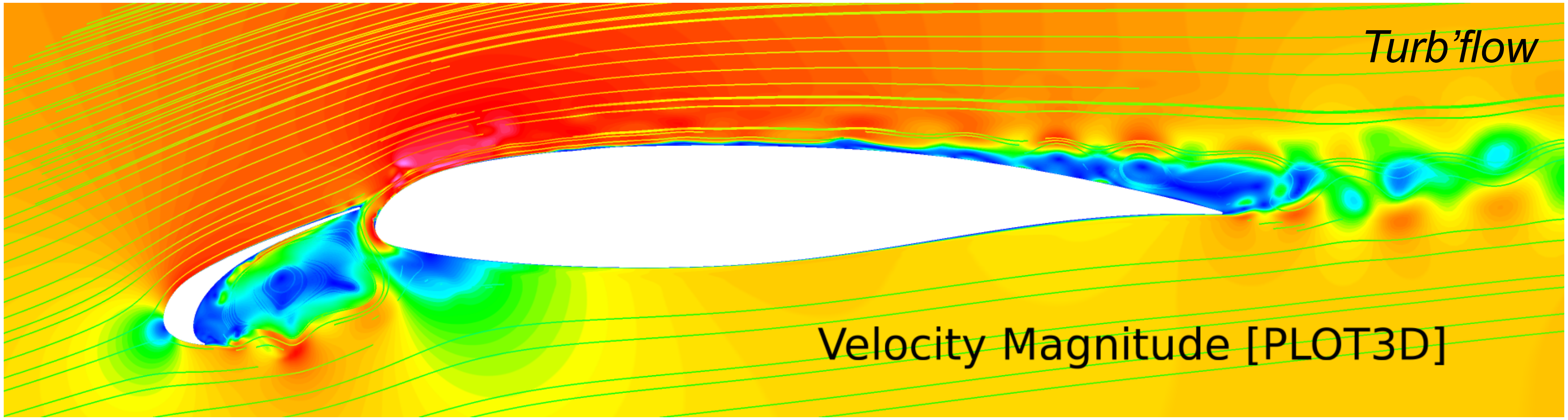
Far-field acoustic pressure

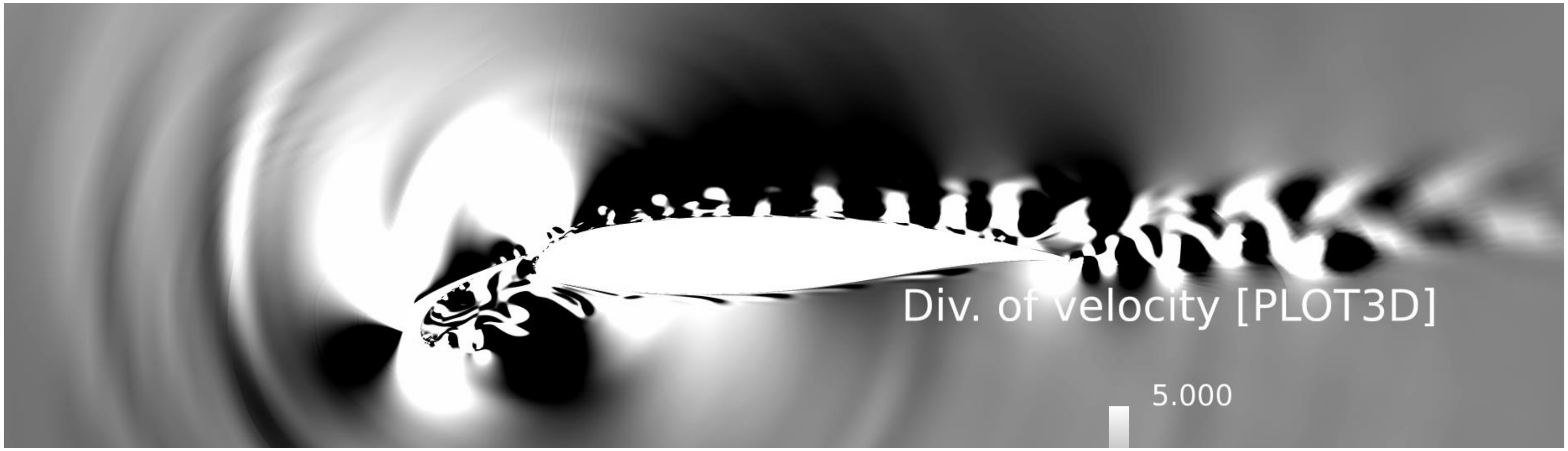




All unsteady simulations capture noise sources
Good direct noise prediction (*Amiet good slope ?*)

High-lift device noise





Good mean aerodynamic performances
Noise radiation dominated by slat sources

Compressible LES of a rod-airfoil (5 10^5)

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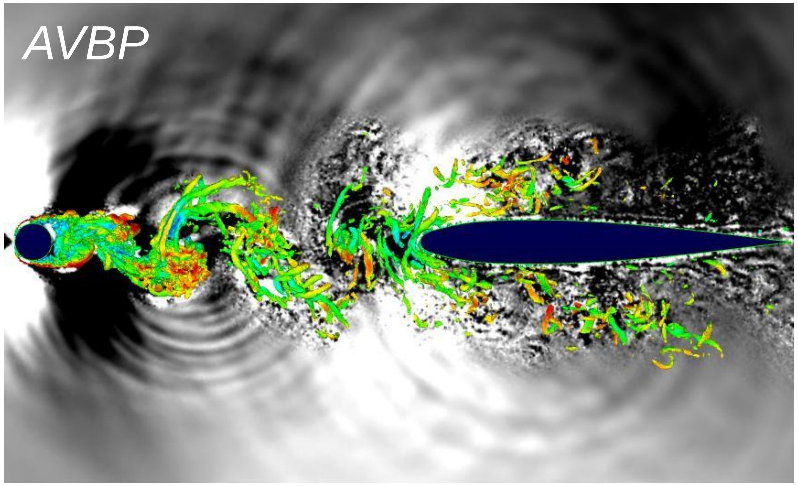

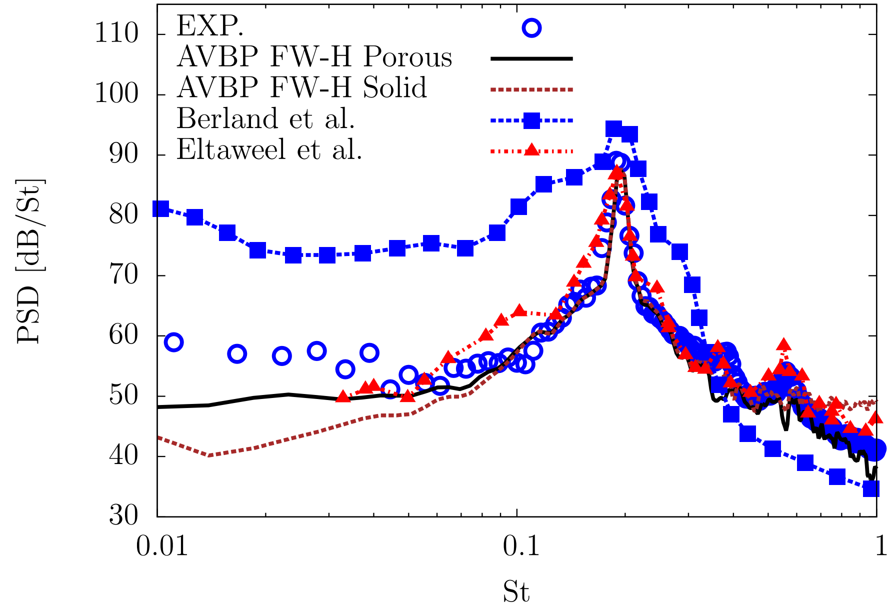

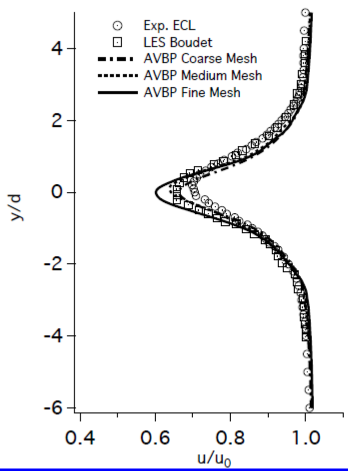

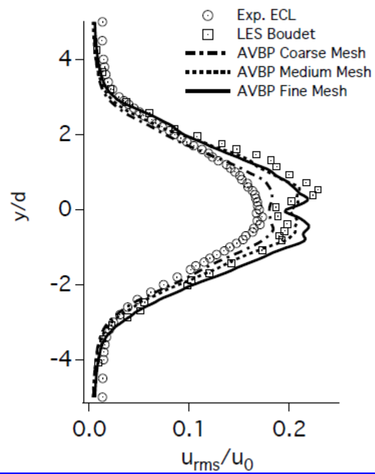

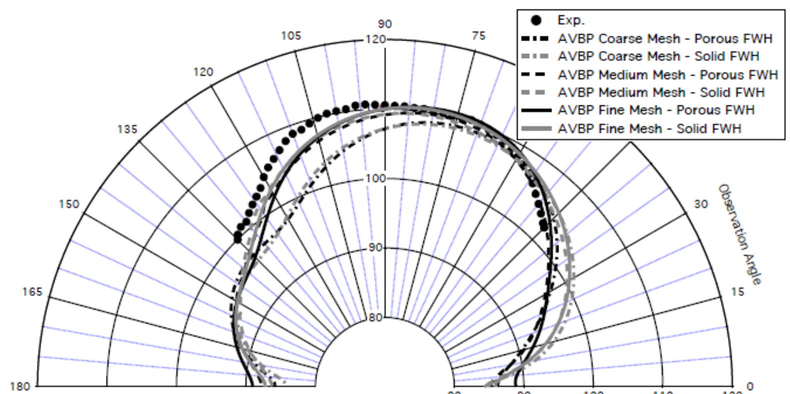

LES of classical benchmark for airframe noise

Excellent overall agreement & noise source localization

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Conclusions

- Several CAA methods have been presented, combining both hybrid and direct noise simulations to yield airfoil noise.

- The hybrid method combining RANS simulations of the experimental set-up, incompressible LES on a restricted domain and an acoustic analogy has been very successful to yield trailing-edge noise in most situations (different operating conditions, tripping, blowing…). Presently nominal flow conditions can be solved efficiently this way.

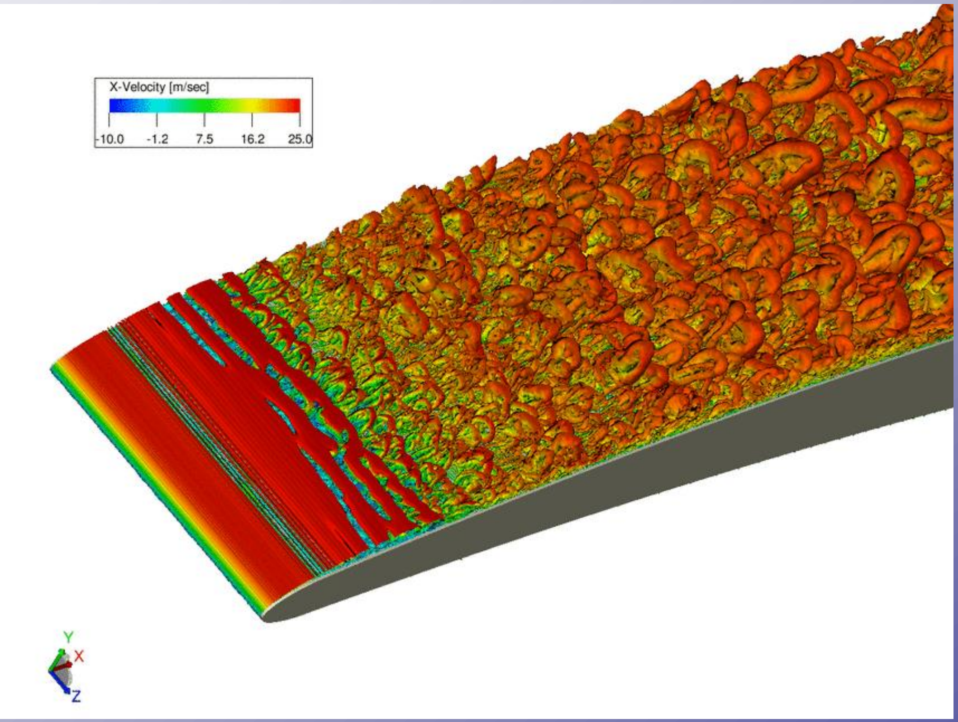
- Yet some discrepancies still exist at high frequencies between the different formulations and feedback mechanisms cannot be captured (the Katana blade).

- Future HPC airfoil predictions will rely on compressible DNS for moderate speed cases ($Re_c \sim 10^5$) and LES for high speed cases ($Re_c \sim 10^6$). Lower speed cases yield too different flow physics.

- At low Mach number, detailed compressible LBM simulations seem to be a very efficient method to yield the direct noise signature in the actual test or installed conditions.

- More cores are needed for higher Re_c on realistic geometries (blades)

Thank you



More Complex Cases

Low speed fans:

Msc, PhD: D. Lallier-Daniels
PhD: S. Magne
Post-doc: M. Sanjose

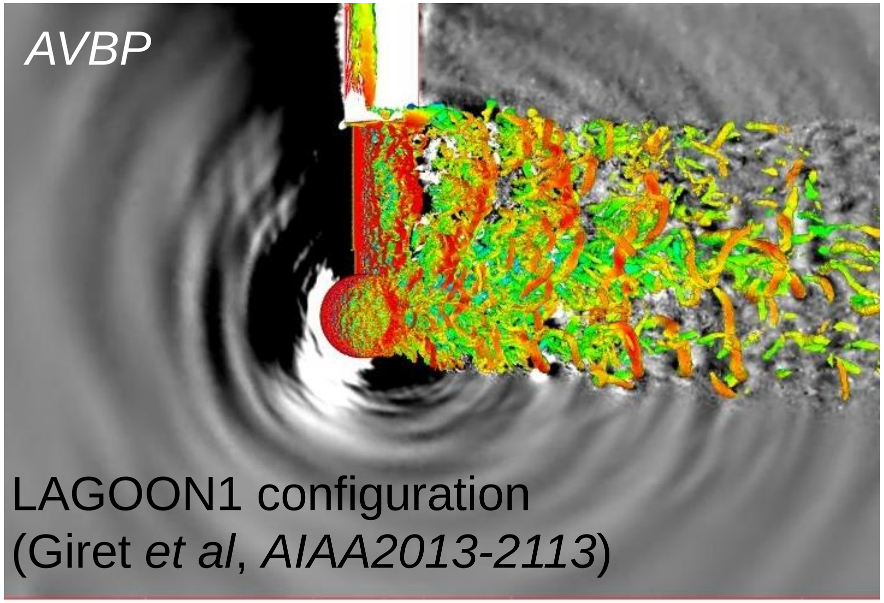
High speed fans:

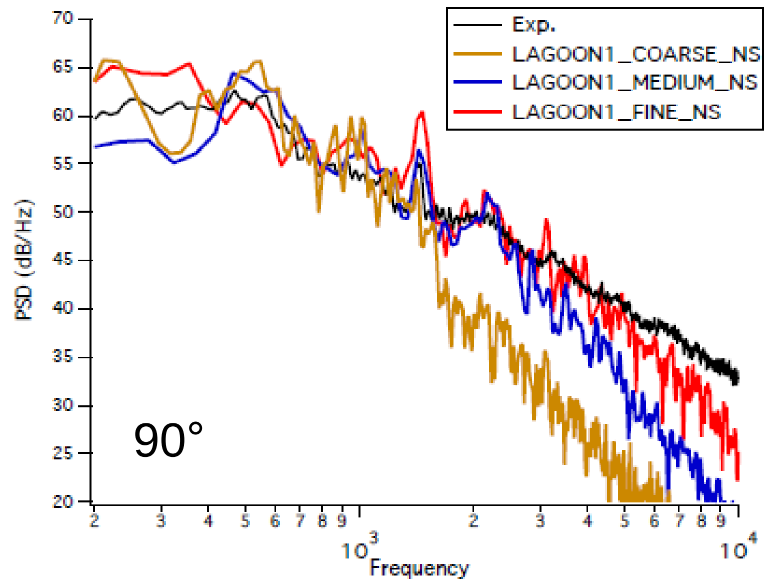
Msc: L. Sauvageot, I. Kernemp
PhD: J. de Laborderie
Post-doc: L. Soulat
Post-doc: H. Posson

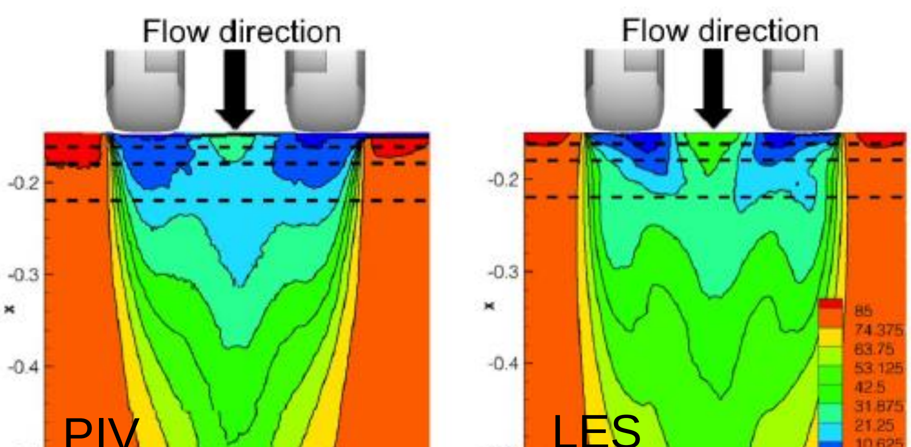
Landing gear:

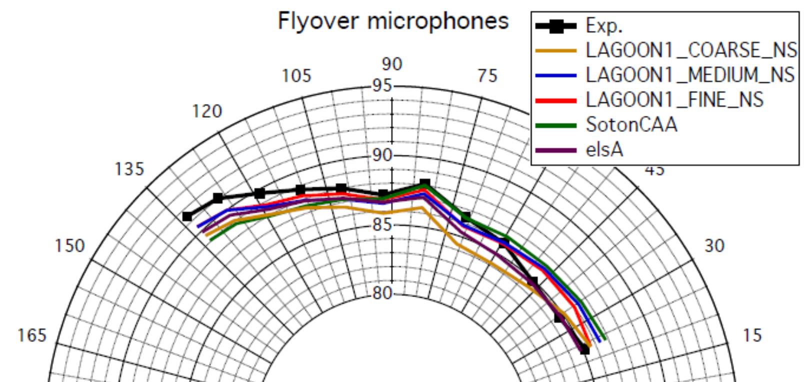
PhD: J.C. Giret

LES Prediction of landing gear noise



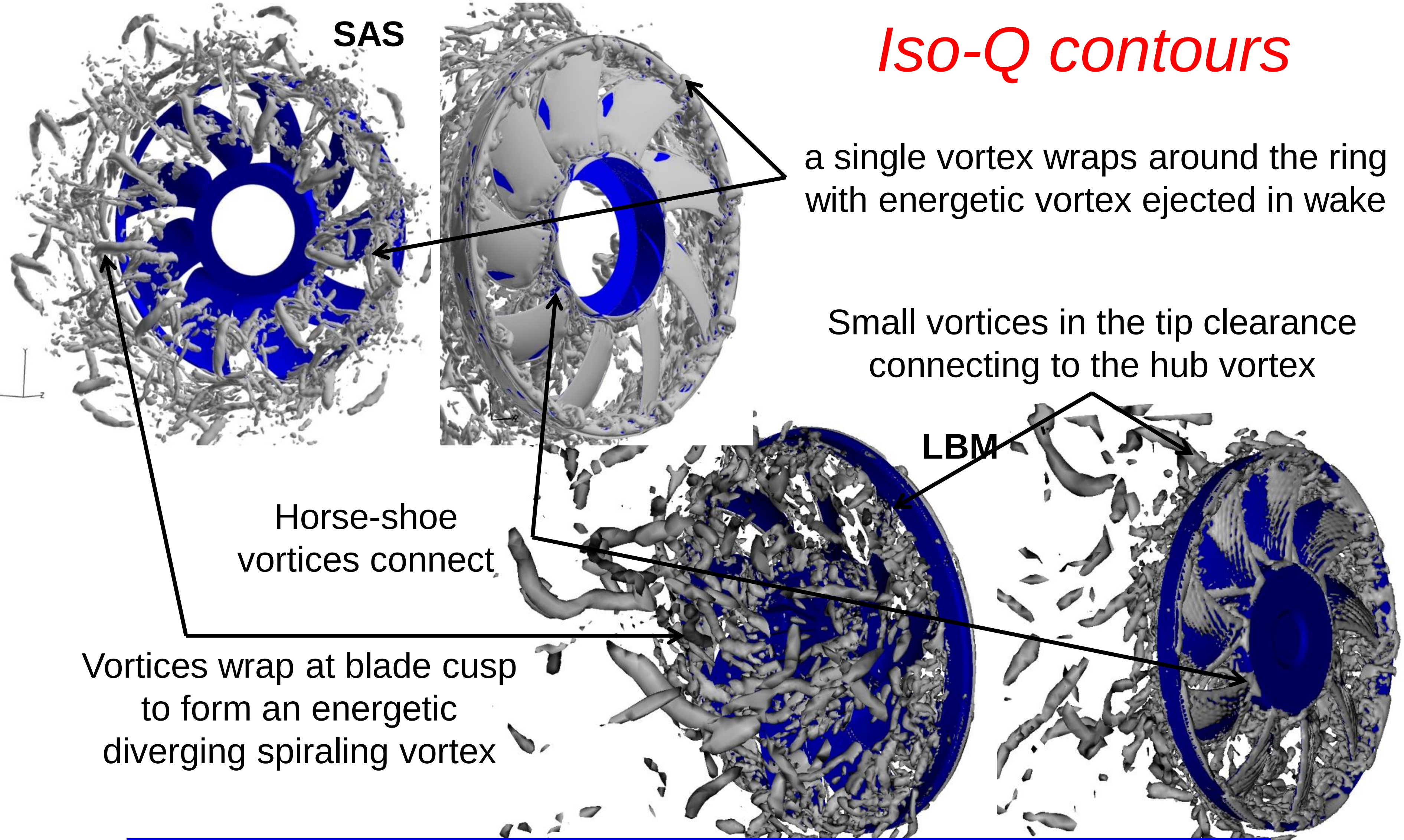






Excellent overall agreement & noise source localization

Low speed fan wake topology



Rich structures from both hub and tip clearance

CROR aerodynamic URANS results

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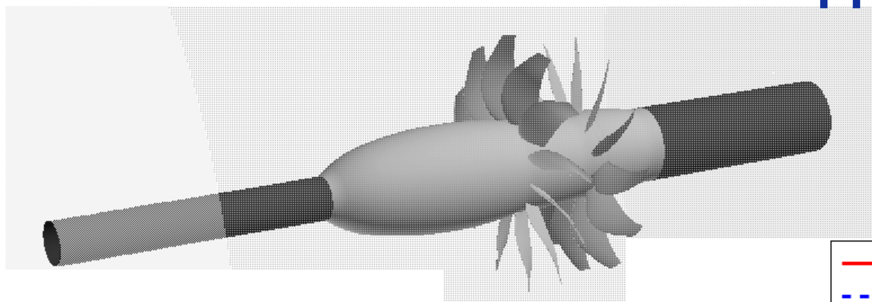
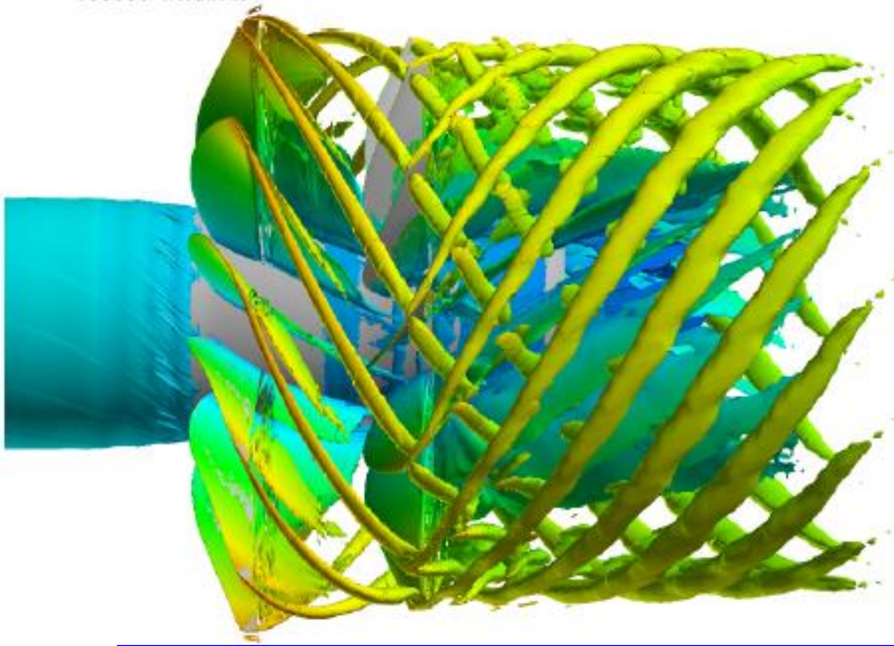
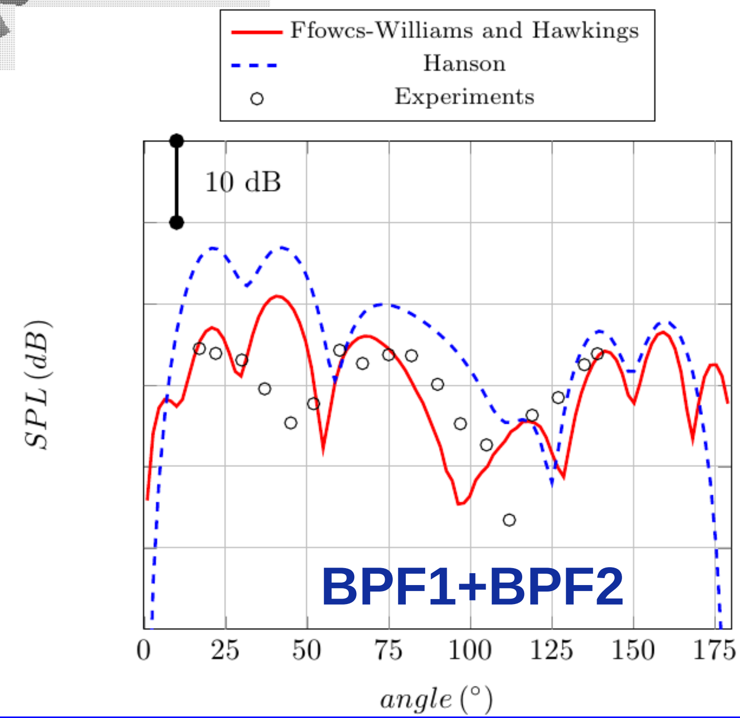
Approach conditions on modern cropped CROR

Turb'flow







Strong wake-interaction on R2 and potential interaction on R1
Strong tip and horse-shoe vortices: secondary sources
Good comparison with NASA experiment

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LES of a reduced compressor stage

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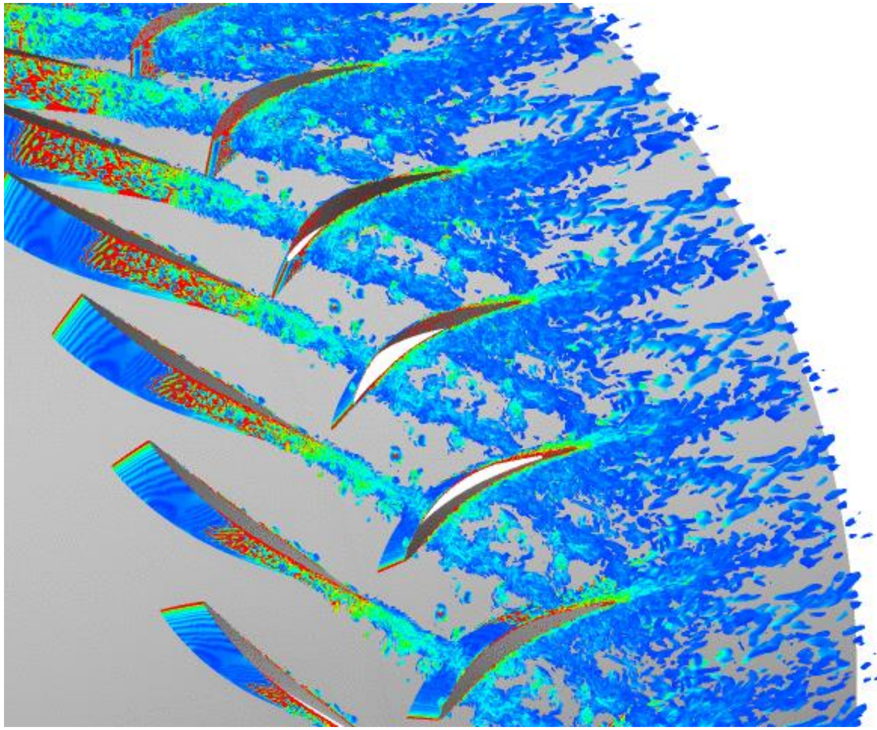
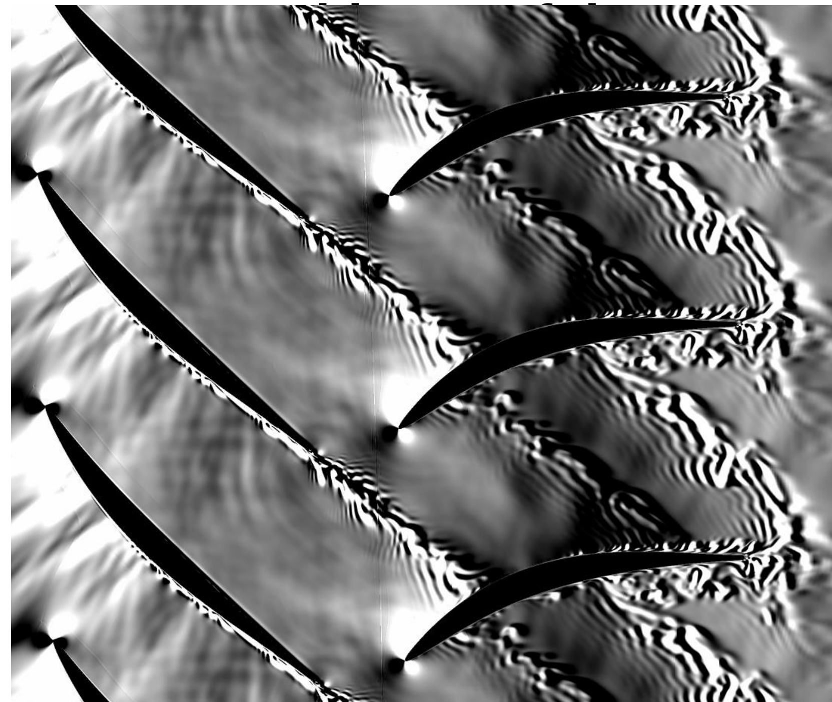
Q factor colored by vorticity magnitude



Turb'flow

Mean pressure fluctuations

Dilatation field



Pressure side

Rotor blade SS transition triggered by adverse pressure gradient
Stator vane SS transition located at a fixed position (50% chord)
Main dipolar radiation at the leading edge

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