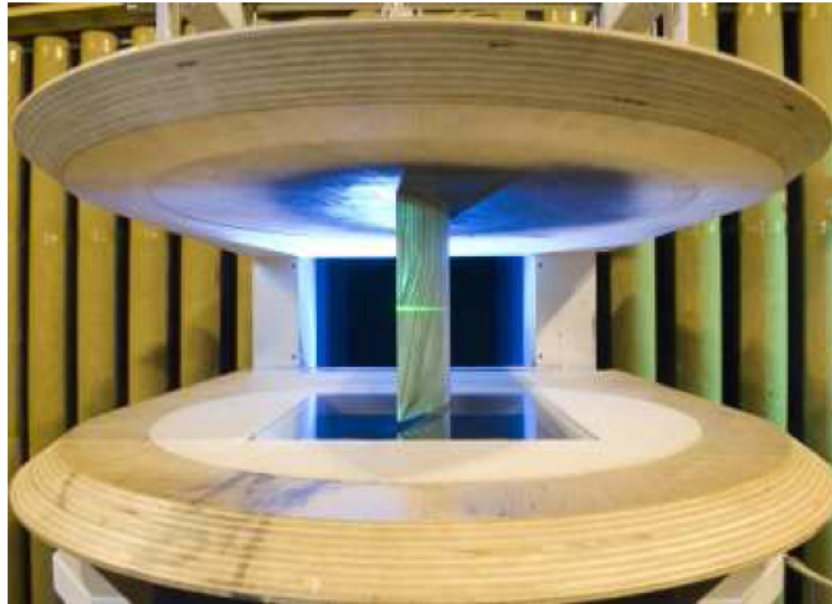




Tip clearance flow measurements and computations

**Trilateral Workshop
On Computational
Experiments in
Aeroacoustics**



**Светлогорск
Россия
23-24.9.2010**

**Marc C. Jacob, Jérôme Boudet, Joëlle Caro
and also: J. Grilliat, E. Jondeau, R. Camussi**

*Centre Acoustique du LMFA, UMR CNRS 5509,
Ecole Centrale de Lyon - University Claude-Bernard Lyon I, France*

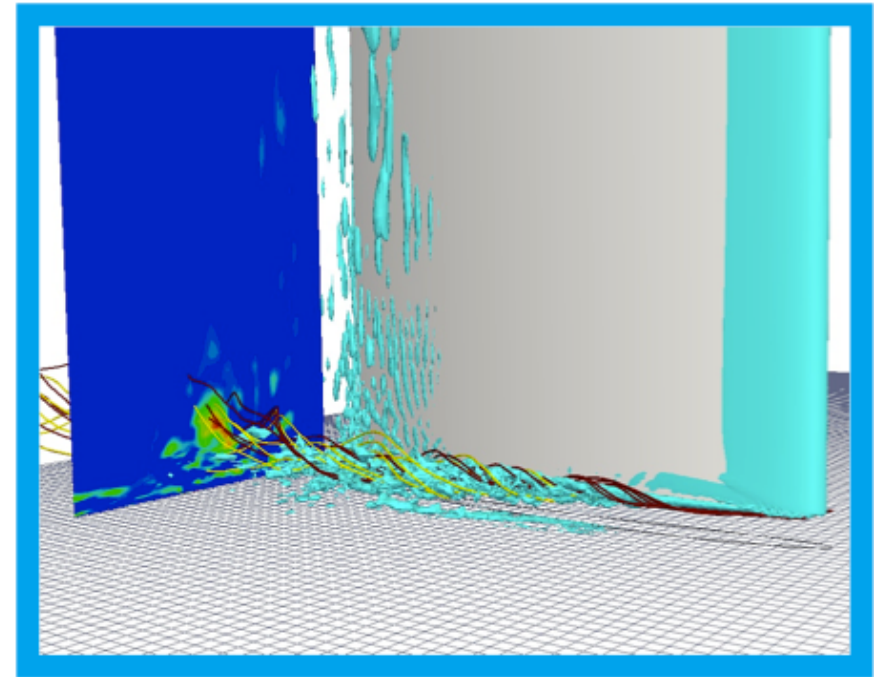
*This work has been funded by the European Community as part of the 6th Framework
Project PROBAND n° AST4-CT-2005-012222.*

Université Claude Bernard

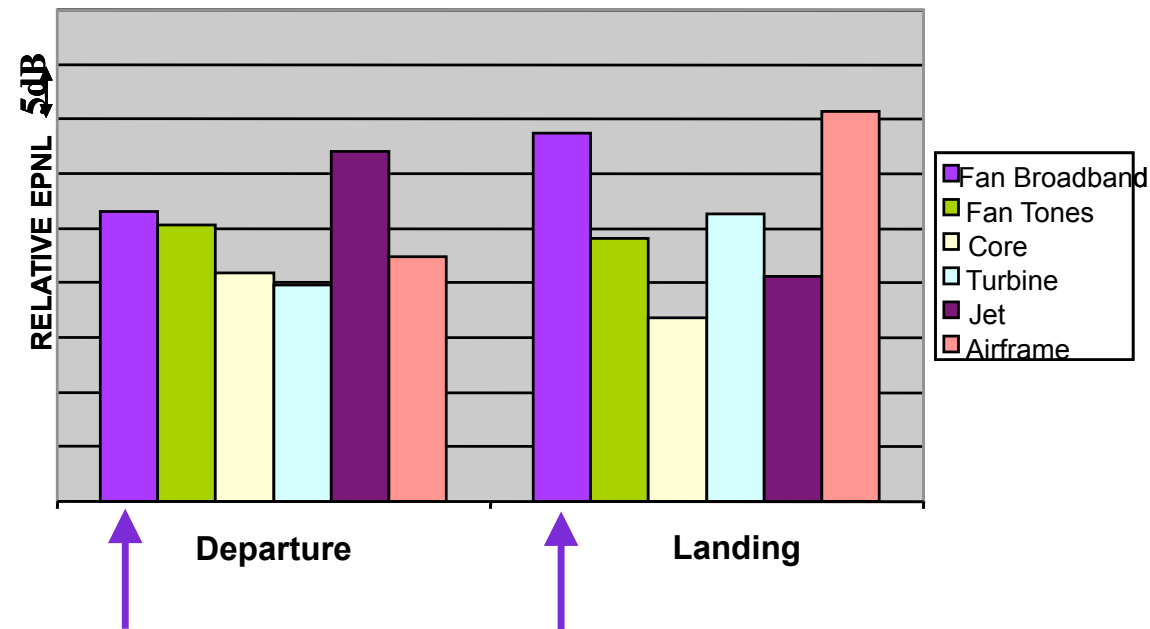


Lyon 1

- **Context and Motivation**
- **Experimental Set-up**
- **Exp. Results & conclusions**
- **Computational set-up**
- **CFD – Results**
- **CFD: Conclusion & Perspectives**



Context



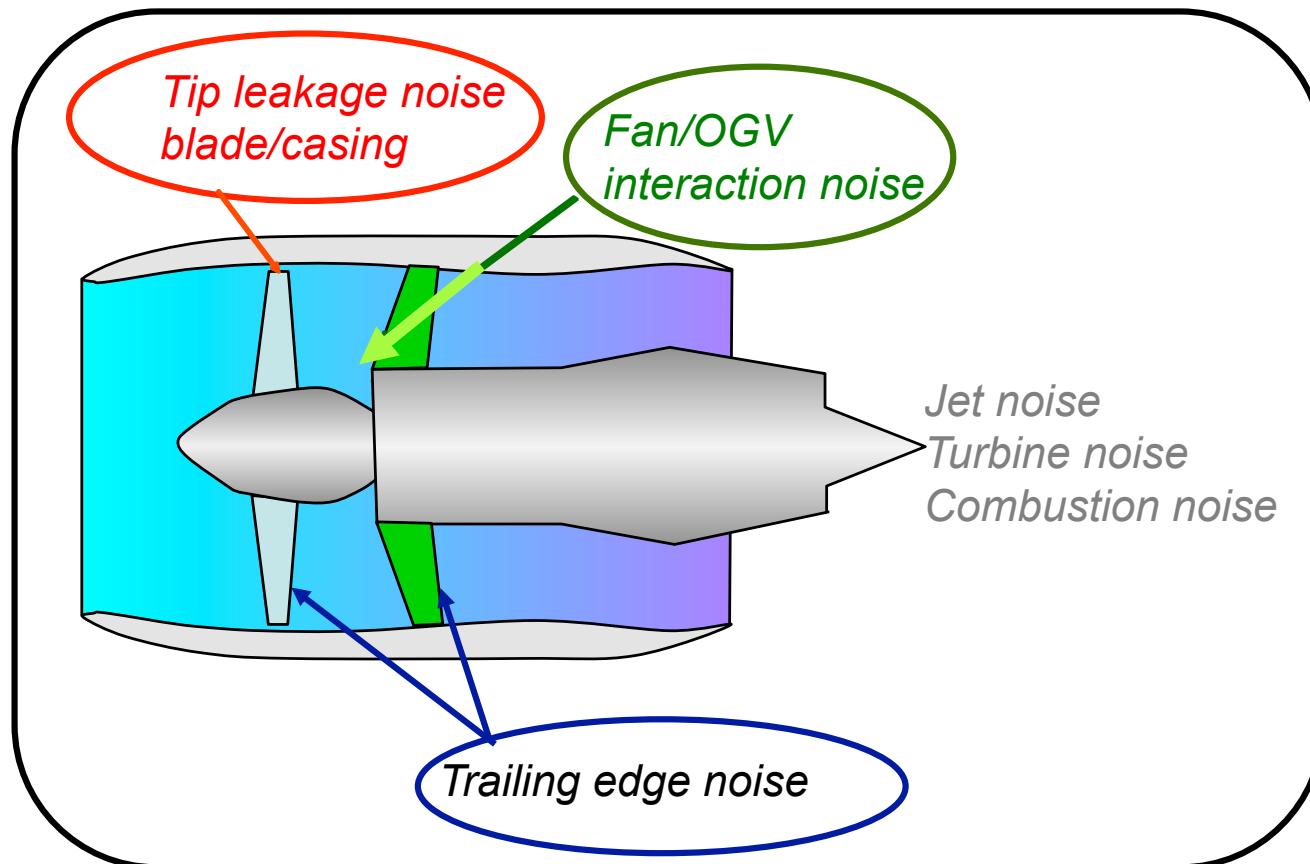
Fan broadband noise

Turbomachinery context: present situation

- RANS used for aerodynamic design
- far too complex for LES, DES ...
- recent efforts to predict tones using unsteady RANS
- broadband noise estimated by empirical extrapolation

EU-project *PROBAND*

- Semi-analytical broadband noise modelling +RANS
- Advanced numerical Simulations (LES, DES + CAA) for broadband noise predictions
- Laboratory experiment for model design and Validation



Experimental set-up: overview

Single non rotating airfoil Experiment

(anechoic high speed subsonic wind tunnel ECL/LMFA)

Surrounding flow

- flanged jet
- potential core

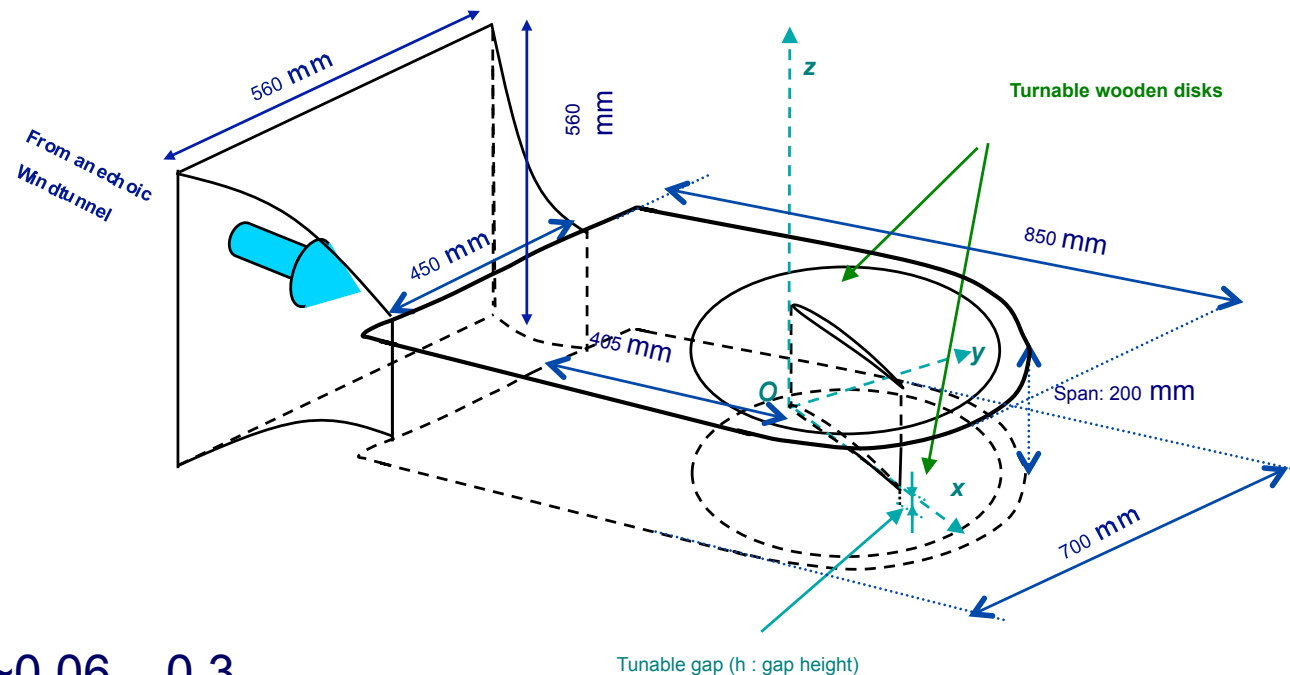
Airfoil: NACA 5510

- Chord: 200 mm
- Span : 200 mm
- Thickness e : 20 mm
- High camber (5%)
- Low Mach number $M \sim 0.06 - 0.3$
- High Reynolds number $Re \sim 2.7 \times 10^5 - 1.3 \times 10^6$

Reference configuration:

$\alpha = 15^\circ$; $h = 10$ mm; $U_0 = 70$ m/s

$Re_c = 9.6 \times 10^5$; $M \sim 0.2$; $h/c = 5\%$; $e/h = 2$



Experimental set-up: overview

Single non rotating airfoil Experiment
(anechoic high speed subsonic wind tunnel ECL/LMFA)



Flow characteristics, Cross validation, & correlations

- Wall pressure measurements
- PIV measurements
- Hot-Wire Anemometry (single and cross-wire)
- LASER Doppler Anemometry

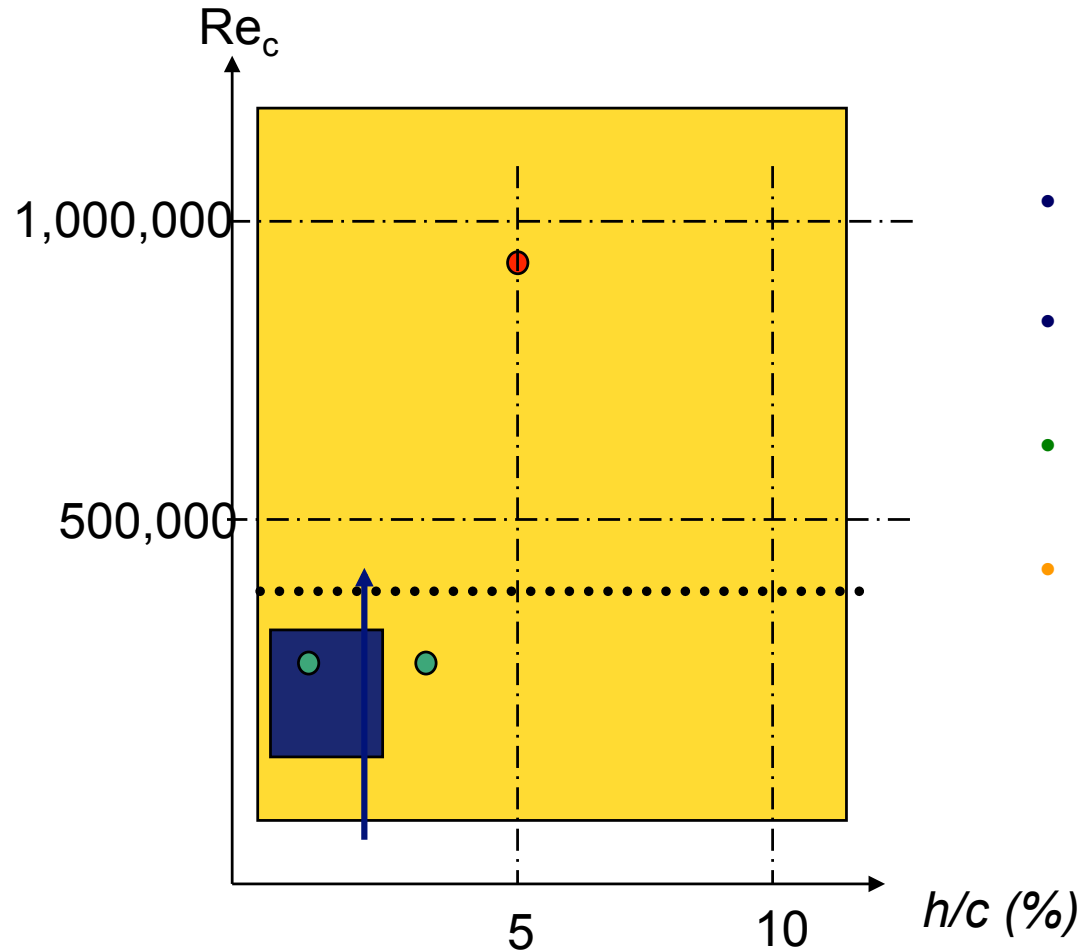
Acoustic measurements

- Directivity
- Spectra

Related Publications

- Main results: Jacob *et al.*, *Int. J. Aeroacoustics*, 9(3), (2010)
- And also:
 - Cross-wavelet analysis: Camussi *et al.*, *J. Fluid Mech.*, to appear, (2010)
 - Analytical model of fan tip source: Grilliat *et al.*, AIAA- paper 2008-2845, (2008)

Parametric study

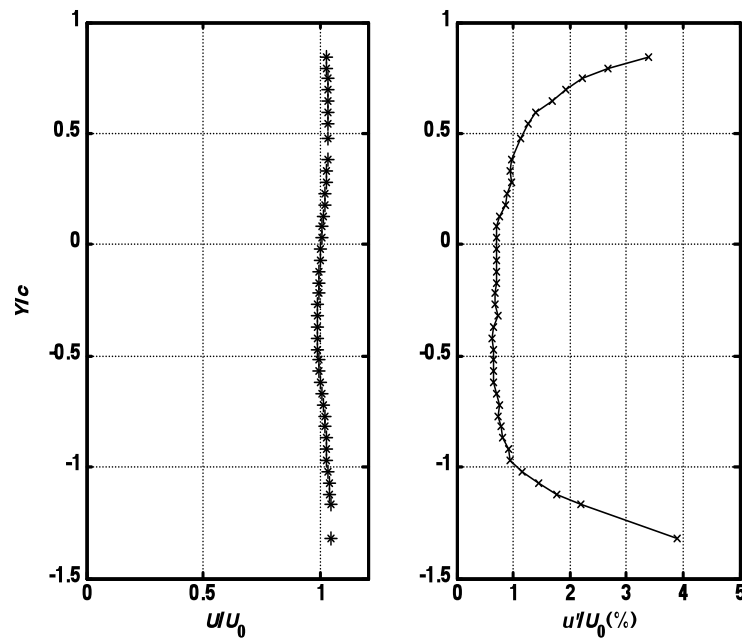


- Bindon (1986-1989) 
- Virginia Tech (1998-2006).....
- Fukano & al. (2003) 
- Present experiment (2007)

● *reference configuration*

*most results
shown hereafter* →

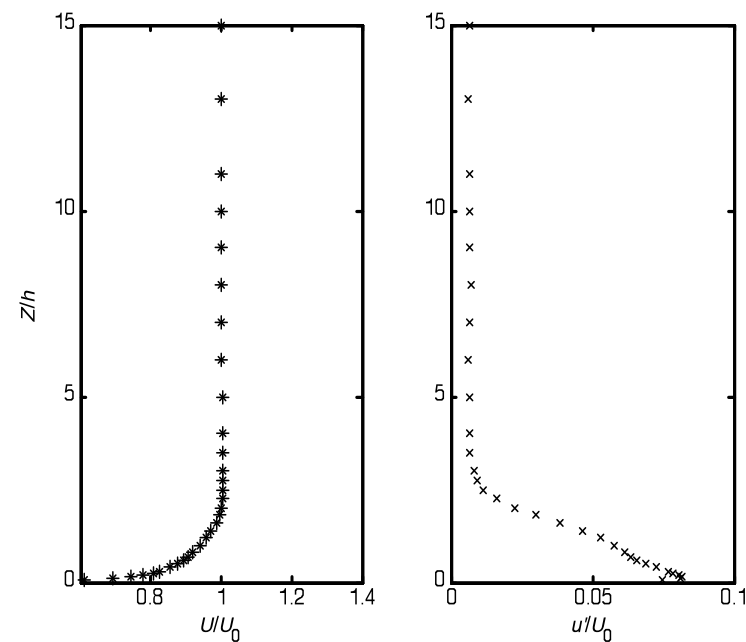
Incoming flow at mid-span



$$u'/U_0 = 0.7 \%$$

Outside shear layers

TBL of incoming flow (half a chord upstream)

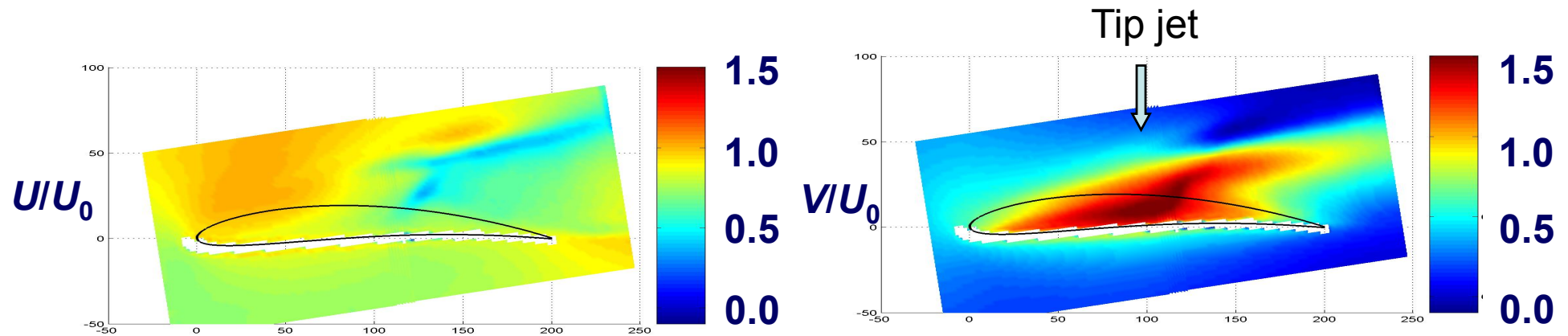


$$\delta = 18 \text{ mm}, \delta^* = 1.4 \text{ mm},$$

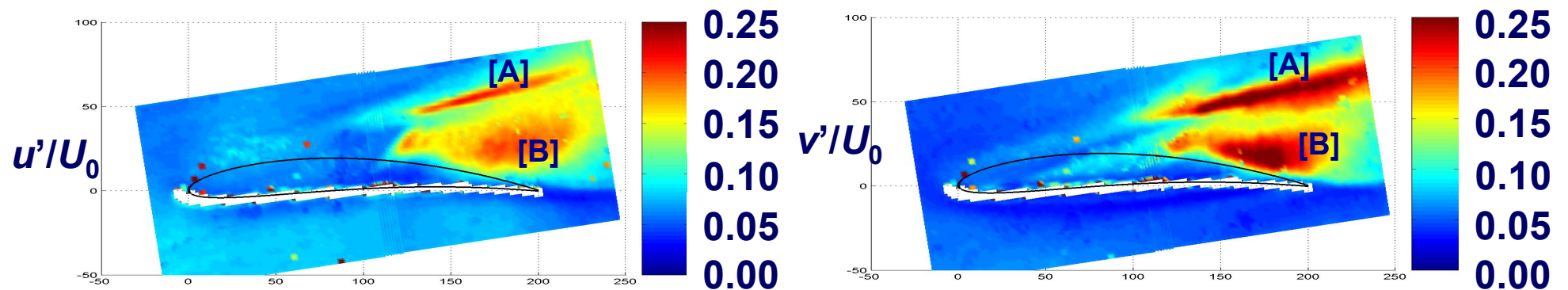
$$\max. u'/U_0 \sim 8\%$$

Main Results: PIV flow fields

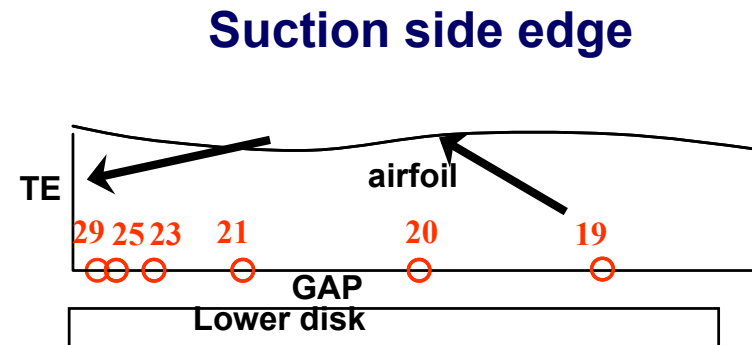
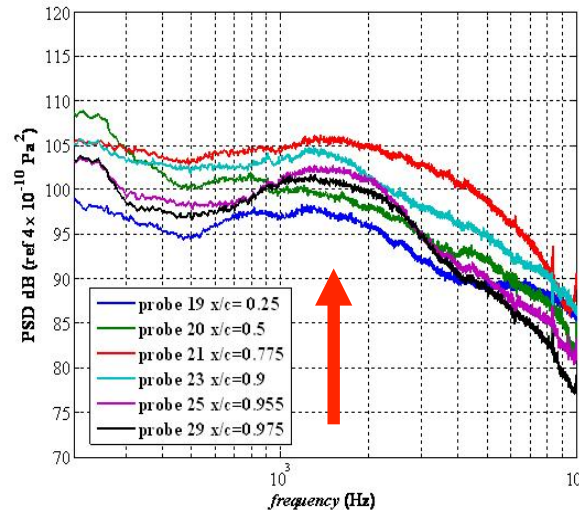
Reference configuration : $h = 10$ mm, $\alpha = 15^\circ$, $U_0 = 70$ m/s, $z = 5$ mm



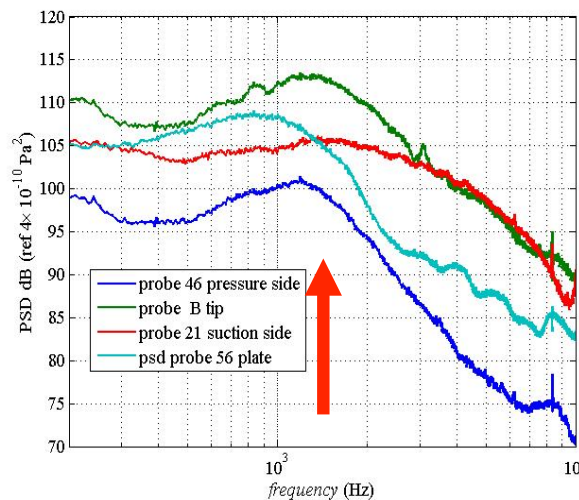
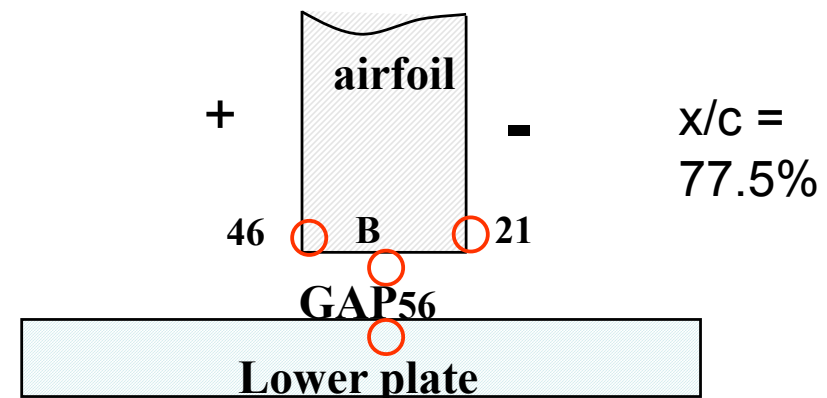
U deceleration – momentum leaves the plane



Main Results: Unsteady wall pressure



Gap at $x/c=0.775$

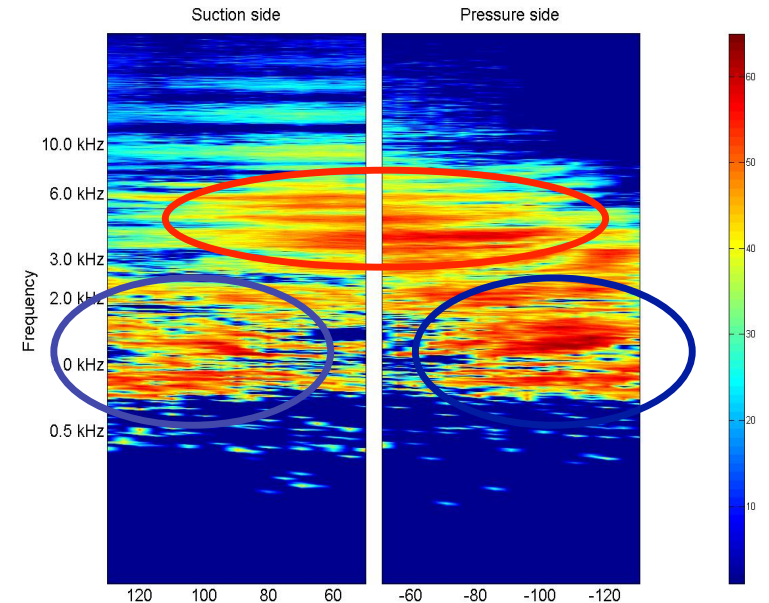
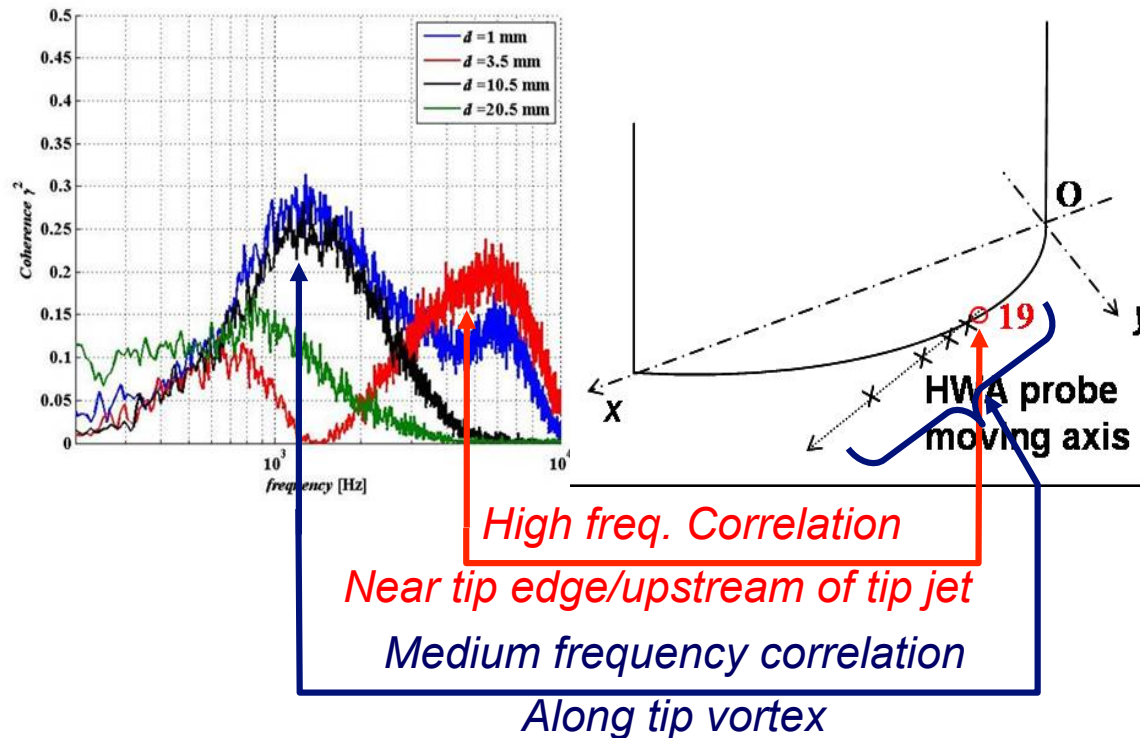


Pressure hump: 0.5 – 3 kHz

Max: $St_c = fc/U_0 \sim 4$

$(St_j = fh/U_{max} = 0.14)$

Main Results: Far field directivity

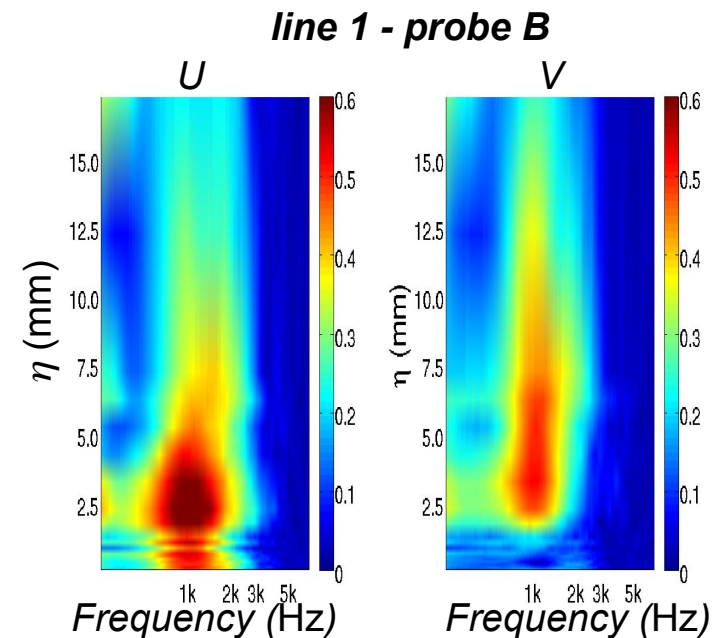
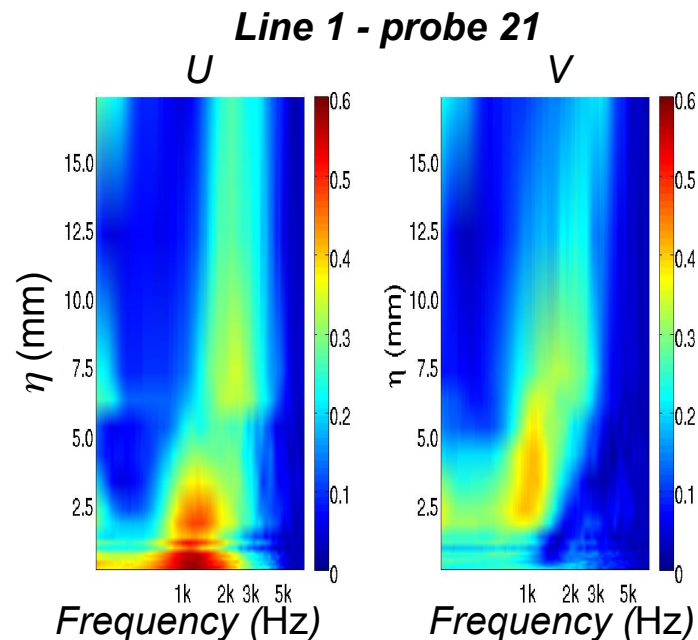
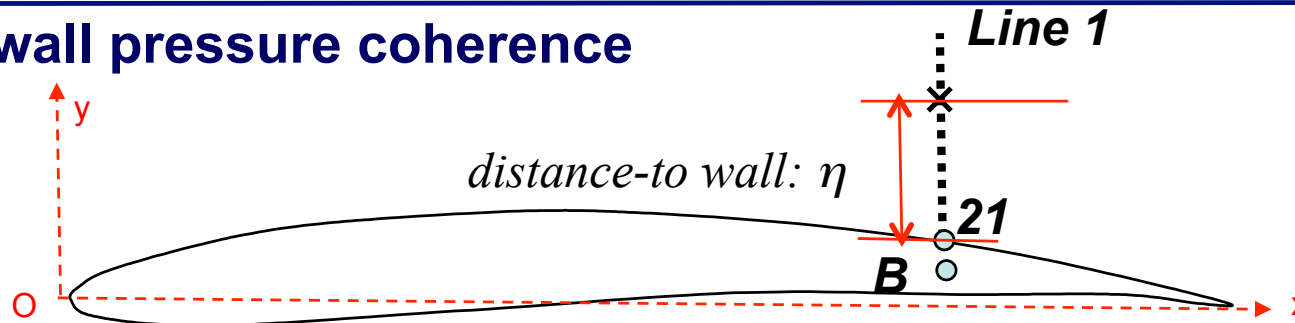


3kHz – 7 kHz → Downstream U_0^{7-8} ➤ jet noise source: tip jet

0.7 – 3 kHz → Upstream U_0^5 ➤ Tip/TE noise source

Trailing Edge scattering

• LDA – wall pressure coherence



Values very high (0.6)

Highest values : probe 21 => 1kHz , at the wall

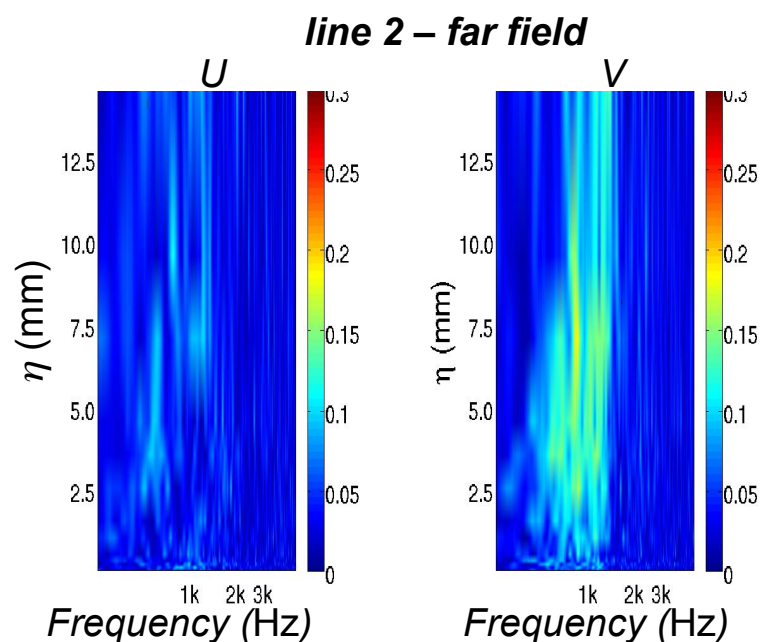
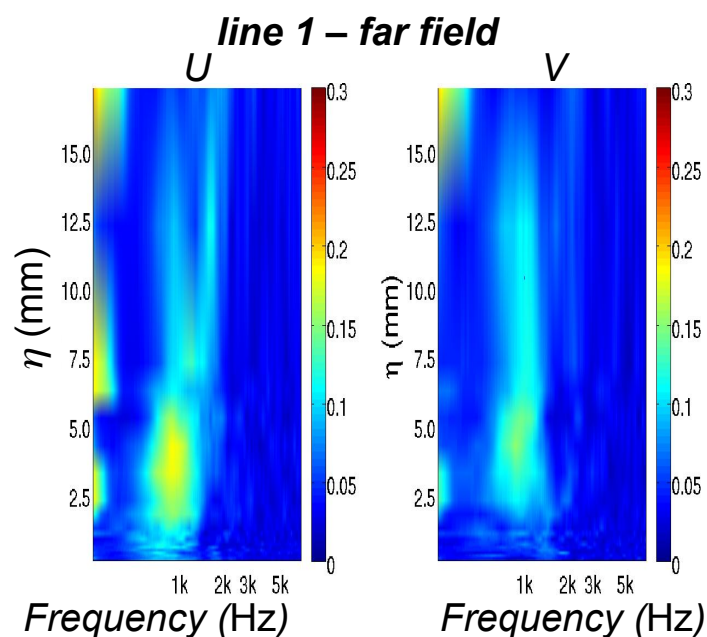
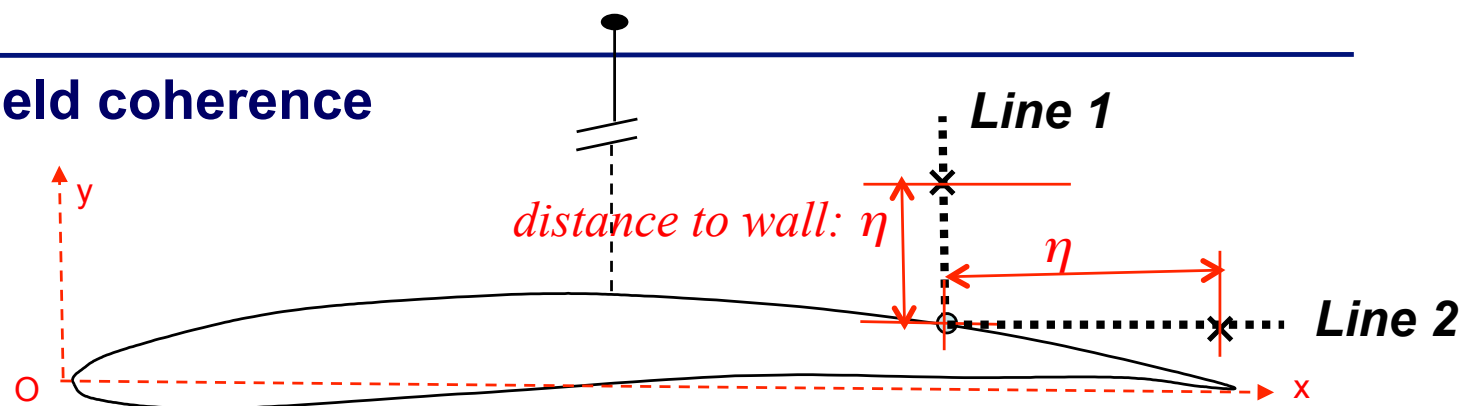
probe B => 1kHz, 2.5 – 5 mm

Region of negative V velocity: structures ejected by tip flow return to the wall

Pressure-velocity correlations



• LDA – Far field coherence



- Velocity : local quantity => Values quite high (0.2)
- Highest values 1kHz & $h \sim 2.5 - 5$ mm (negative V) => TE corner source ?
- Similar to coherence (LDA, probe B): eddies generated in the gap radiate near TE



Cross-conditional wavelet analysis

Wavelet transform

$$w^r(t) = r^{\frac{1}{2}} \int f(\tau) \Psi * \left(\frac{t - \tau}{r} \right) d\tau$$

Ψ : Mother wavelet (Battle-Lemarie)

$$LIM = \frac{|w^r(t)|^2}{\langle |w^r(t)|^2 \rangle_t}$$

Local Intermittency Measure (LIM)
(normalized energy)



Event selection criterion

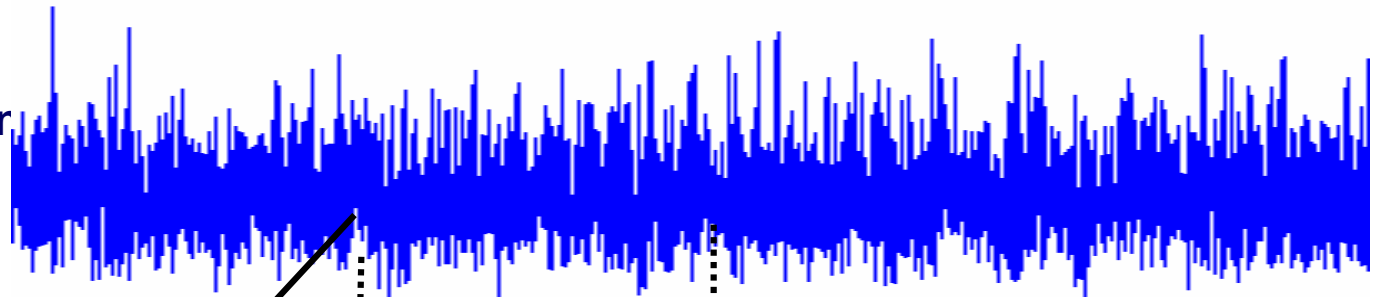


Conditional Wavelet Analysis
(Selection of High *LIM*-level events)

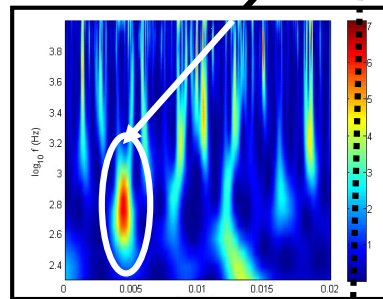
Example: Pressure-conditioned PIV analysis

Camussi et al., *J. Fluid Mech.*, to appear, 2010

Pressure signal Mic. B on tip at ($x/c = 0.775$)

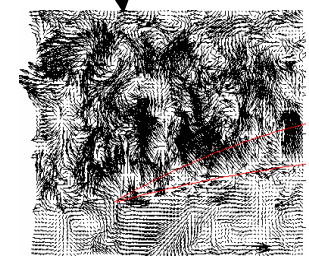
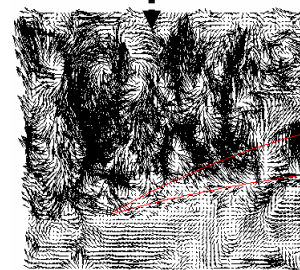
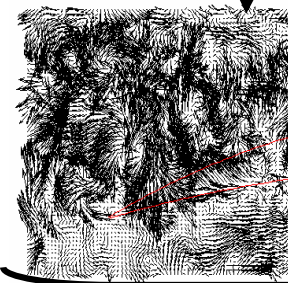


Selection of Pressure events
(60)

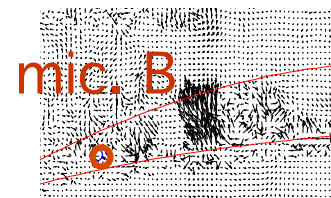


etc ..

Associated PIV snapshots
(60 out of 600)



Conditional Average: Eddies causally linked to pressure event



Experiment-conclusions

- Strong tip flow ($V_{max} \sim 1.5U_0$): cross-stream jet
- Rolls up into tip vortex with two regions of strong turbulent fluctuations ([A] and [B]). Region [A] originates from the plate boundary layer, and is associated with the low axial velocity region
- Tip clearance confirmed as a significant broadband (self-) noise source
- Two source mechanisms:
 - Gap flow ejected as a side jet (high freq.)
 - Gap perturbations scattered by TE/tip corner (medium freq.)
- Two behaviours: small and large gap (+ transition): due to gap bubble
- Analysis confirmed by Coherence and Cross-Conditional Wavelet analysis
- Data base suitable for CFD-initialisation & validation and for analytical modelling

LES Study of the flow: Context

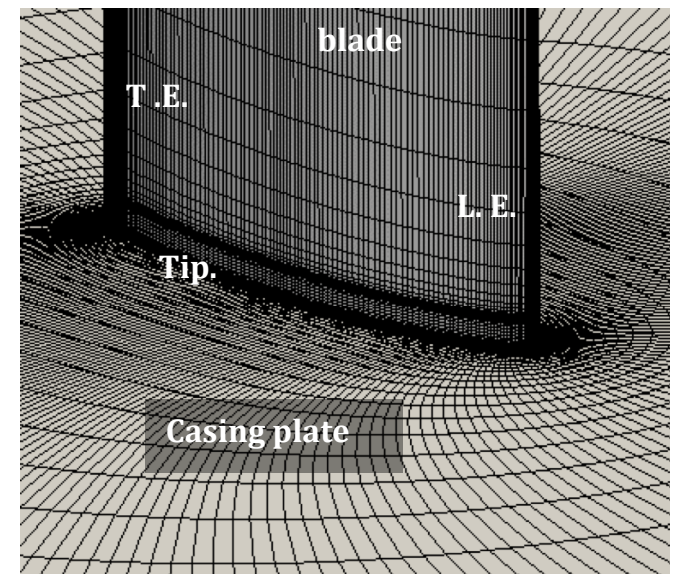
- **Former computations related to the NACA5510 experiment**
 - Gamet et al. (2007), *Fan Noise 2007*, Lyon
→ First attempt of LES computation
 - Boudet et al, (2009) *ETC-9*, Graz
→ RANS Computation
 - Greschner et al, (2010), *Int. J. Aeroacoustics*, 9(3), pp. 329-355
→ distributed TE Noise contribution

- **Turb'Flow solver: ECL / Fluorem in-house**

- Finite Volume discretization of the compressible equations
- LES approach with shear-improved Smagorinsky model (see next)
- Convective fluxes: 4 point centered interpolation, 4th order numerical viscosity
- Diffusive fluxes: 2 point centered
- Explicit time marching with 3-step Runge-Kutta

- **Grid**

- 18 blocks structured (≈ 5 million points), extending over $\approx 8c$ around airfoil
- wall cell height: $\Delta y^+ < 6$ ($\Delta y^+ < 3$ for most of the tip region)
- wall cell length and width: $\Delta x^+, \Delta z^+ < 300$



- **Model for the unresolved subgrid-scales⁽¹⁾**

$$\bar{\mu}_{sgs} = \bar{\rho} (C_s \Delta)^2 \left(|\tilde{S}| - \langle |\tilde{S}| \rangle \right) \quad \left\{ \begin{array}{l} \Delta : \text{filter cut - off} \\ |\tilde{S}| = \sqrt{2 \tilde{S}_{ij} \tilde{S}_{ij}}, S \text{ the rate - of - strain tensor} \\ \langle \rangle : \text{average} \Rightarrow \text{very - large scales} \end{array} \right.$$

→ accounts for the effects of the very-large scales (inhomogeneities, separation structures, vortices...), at moderate cost

- **Very-large scales identification⁽²⁾**

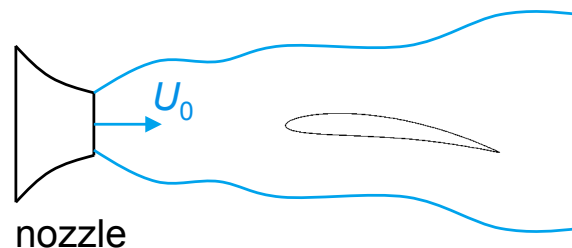
- exponential average
- adaptive Kalman filter

(1) Lévêque, E., Toschi, F., Shao, L., Bertoglio, J.-P., “Shear-improved Smagorinsky model for large-eddy simulation of wall-bounded turbulent flows” *Journal of Fluid Mechanics* 570: 491-502, 2007.

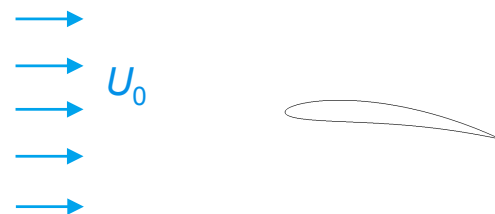
(2) A. Cahuzac, J. Boudet, P. Borgnat, E. Lévêque, “Smoothing algorithms for mean-flow extraction in large-eddy simulation of complex turbulent flows”, *Physics of Fluids*, to appear, 2010.

Mean wall-pressure coefficient (mid-span)

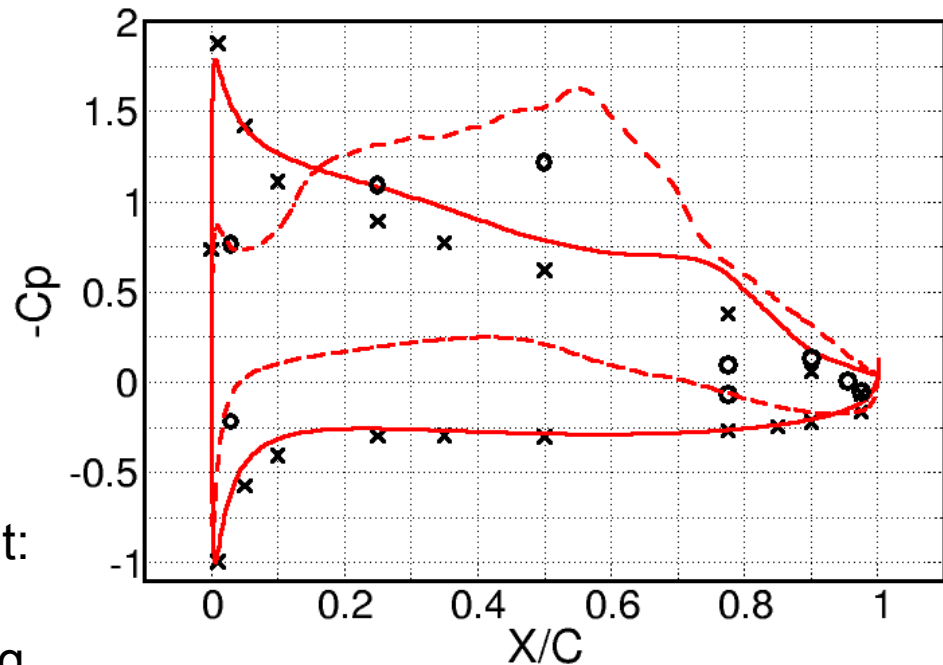
- LES angle of attack adjusted, to replace the experimental jet flow by an infinite free flow
- Calibration criterion: mean wall pressure coefficient at mid-span



Experiment:
jet flow
 $\alpha_{\text{exp}} = 15^\circ$



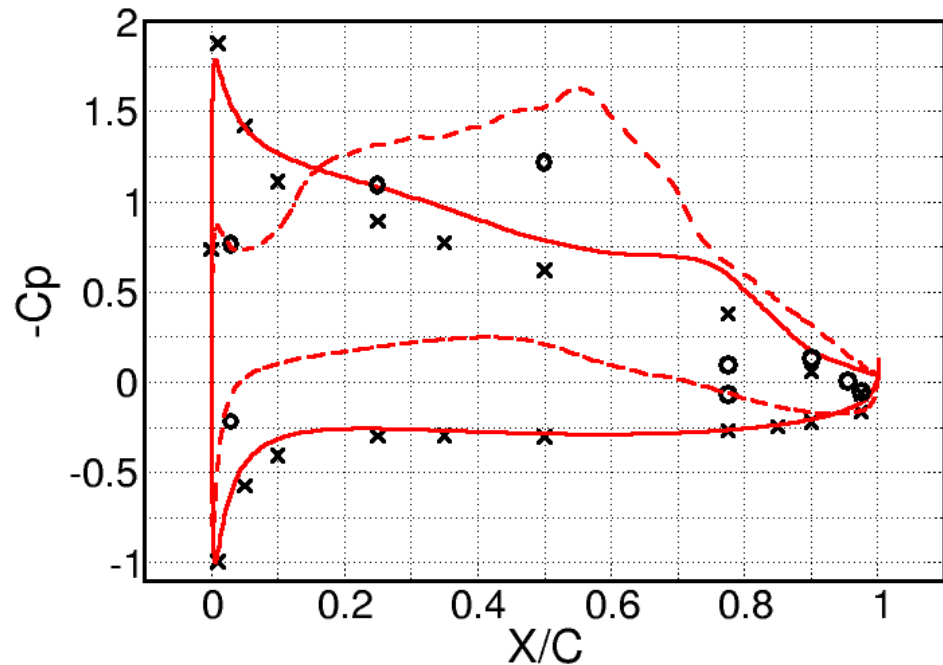
LES:
infinite free flow
 $\alpha_{\text{LES}} = 7^\circ$



x : experiment at mid-span
— : LES at mid-span
o : experiment at tip
- - : LES at tip

Mean wall-pressure coefficient (tip edge)

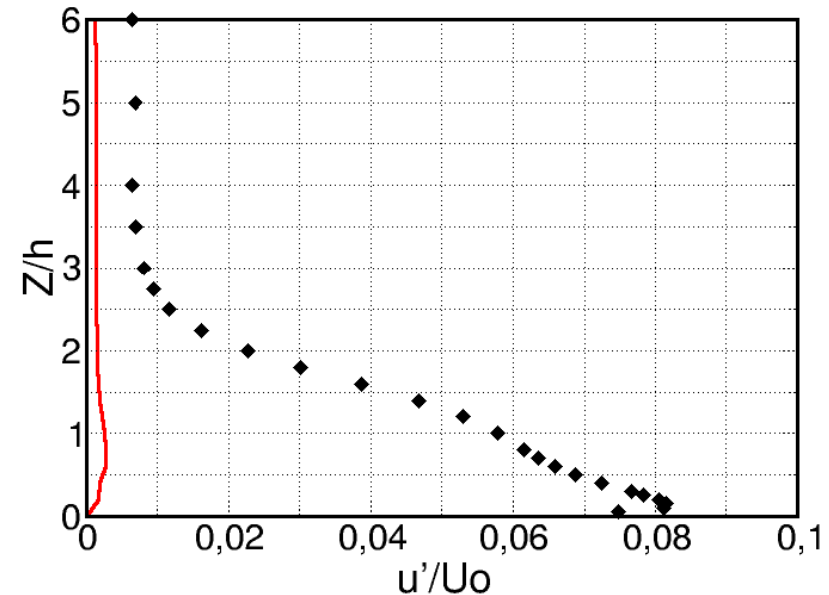
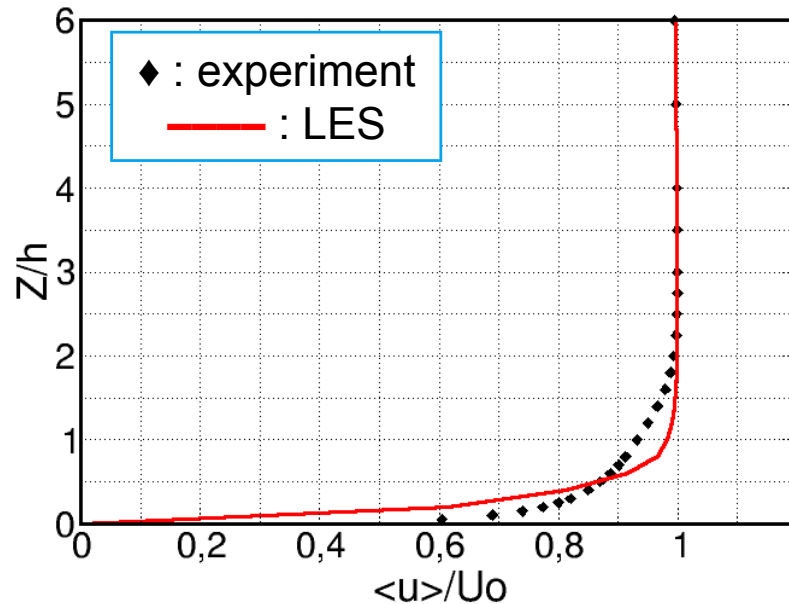
- Tip distribution: no calibration
- Rather good agreement
- Main difference with mid-span: hump of $-C_p$ on suction side
- Effect of the leakage through the gap
- LES confirms the peak at mid-chord, measured on one probe only



x : experiment at mid-span
 — : LES at mid-span
 o : experiment at tip
 - - - : LES at tip

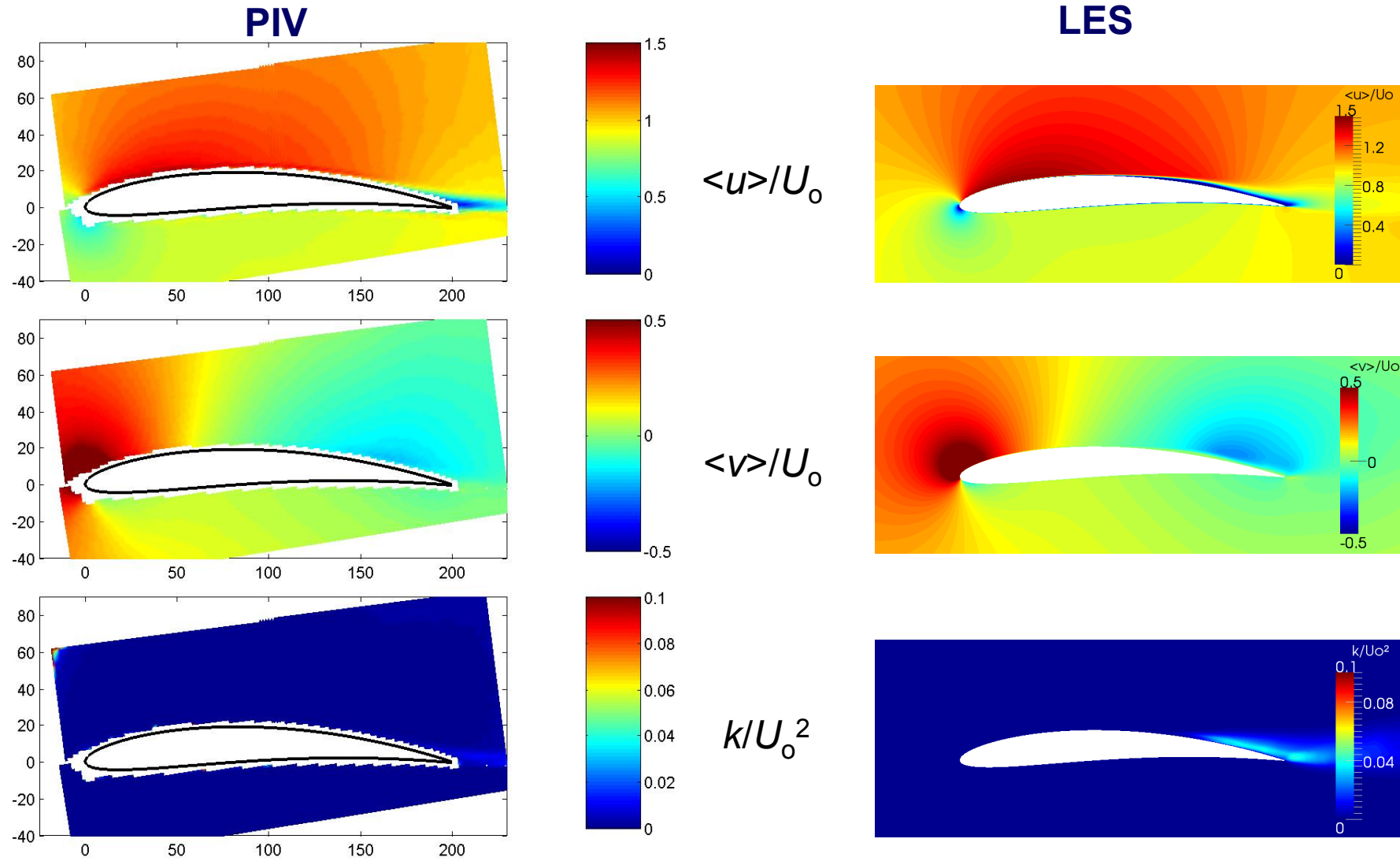
Incoming boundary layer on casing plate

(half a chord upstream of the blade)

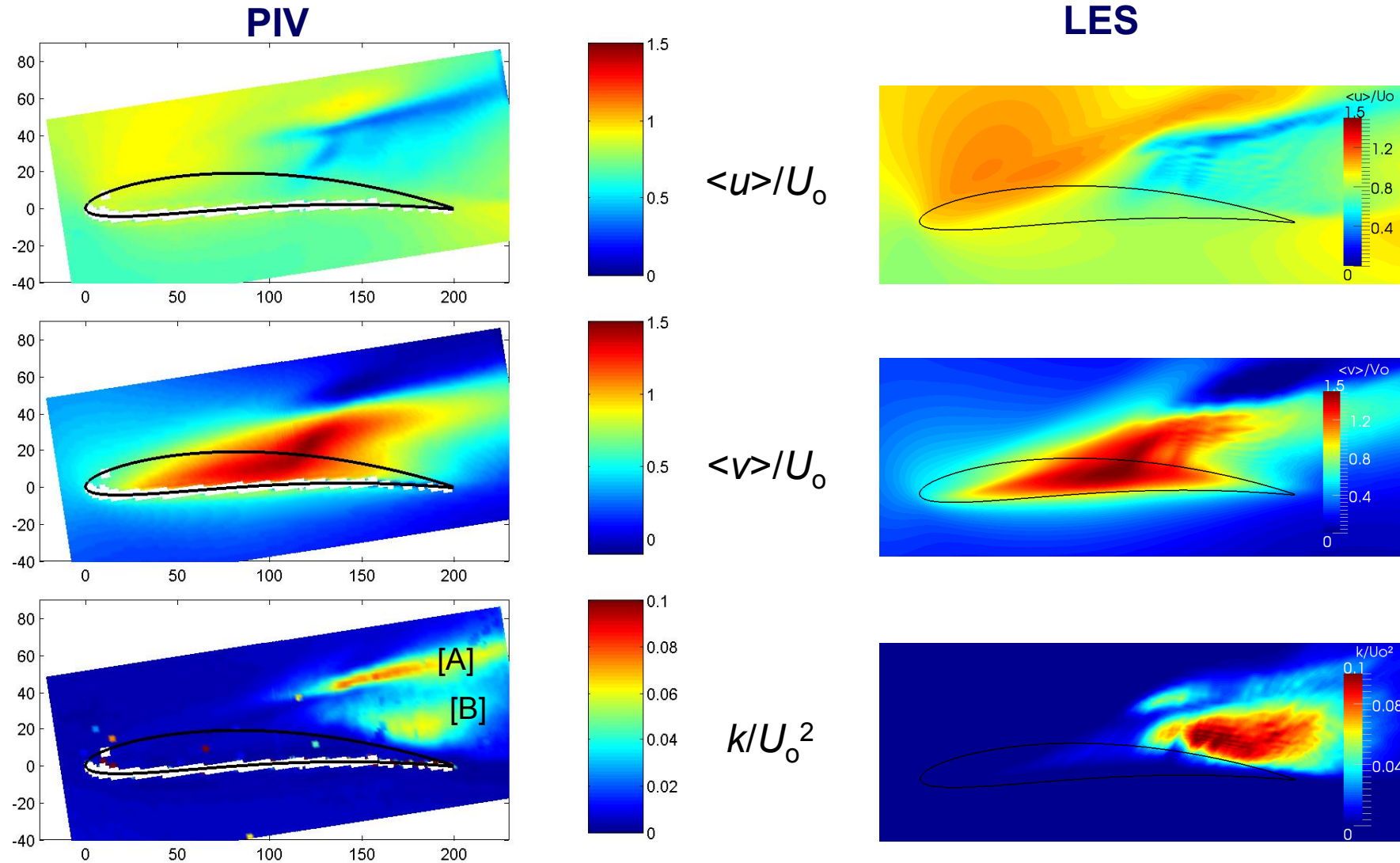


- Steady inflow boundary condition $\rightarrow$ TBL develops through domain
- TBL thickness roughly OK (mean flow) but major discrepancies on fluctuations
- Fortunately, TBL has marginal influence in this tip-flow configuration
- To improve TBL prediction, unsteady turbulent inflow should be implemented

Mid-span flow maps

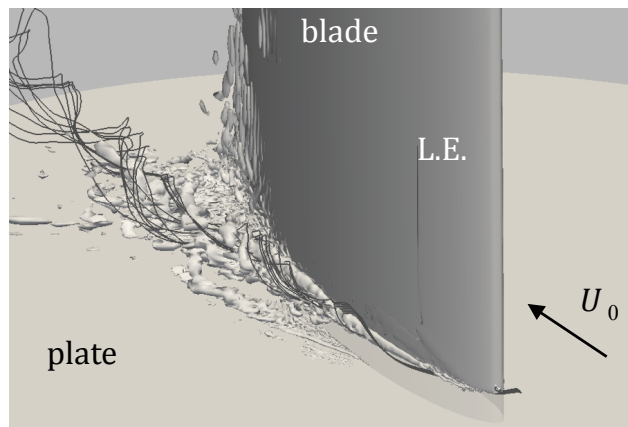


Mid-gap flow maps



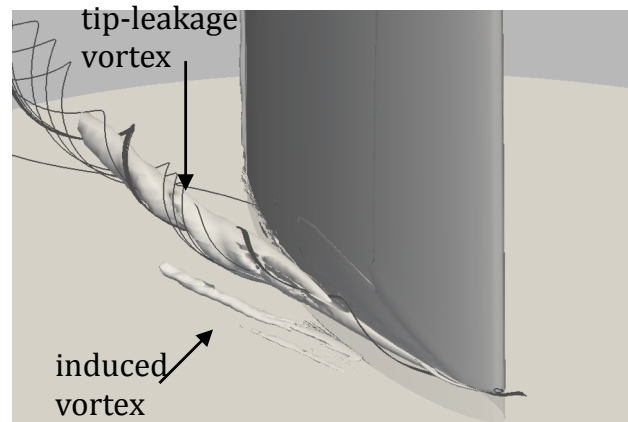
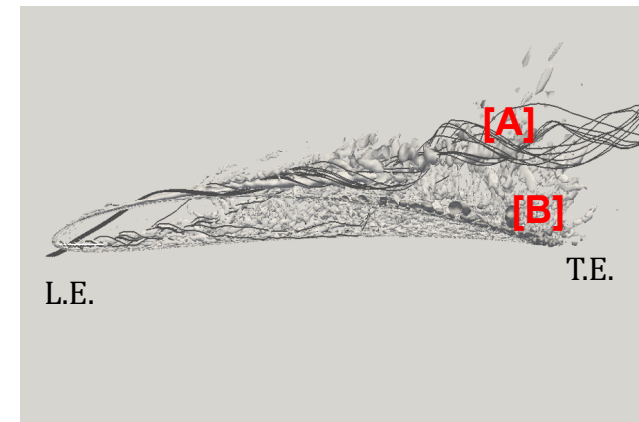
Instantaneous Flow /Mean Flow

global view

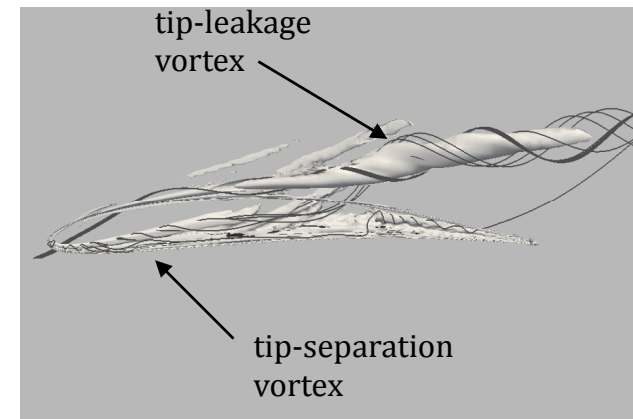


instantaneous

view of the gap, from the plate

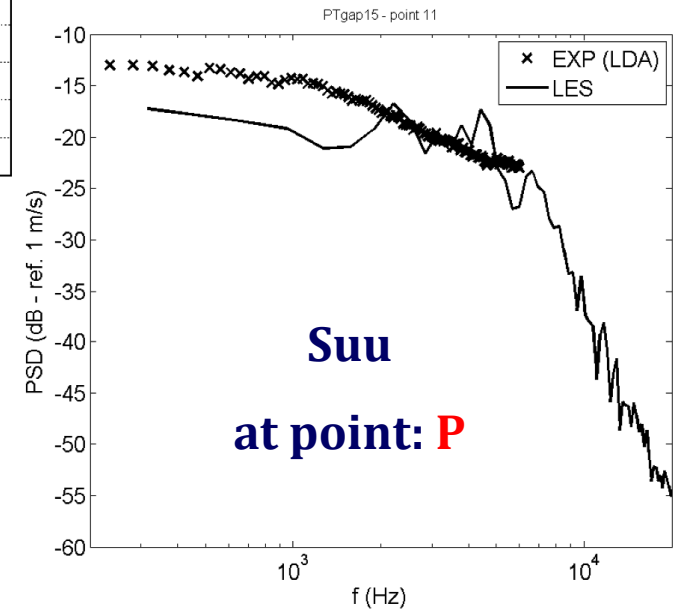
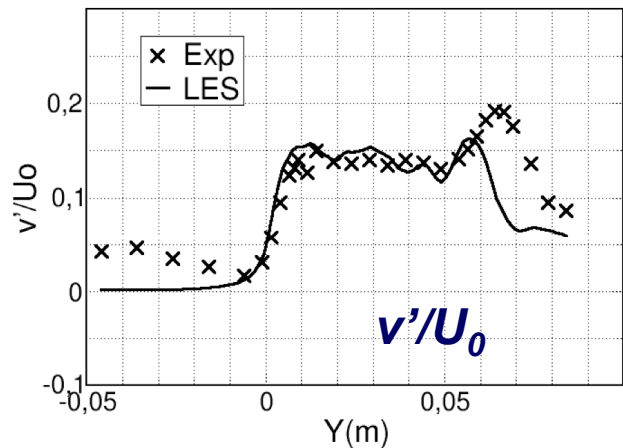
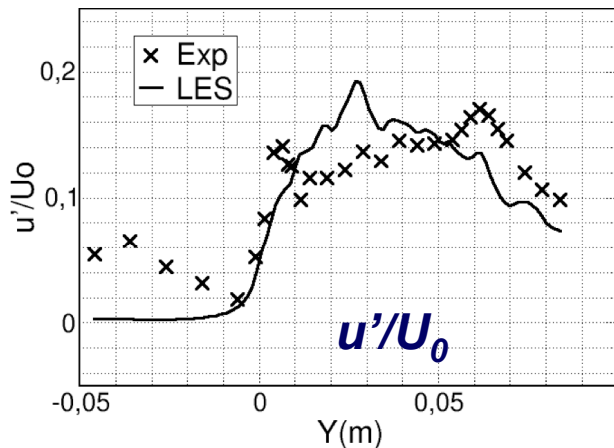
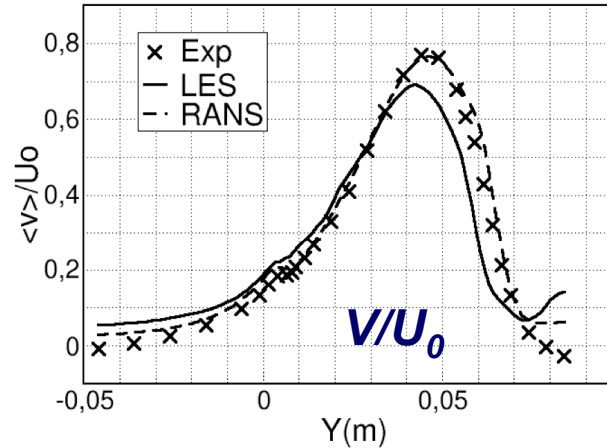
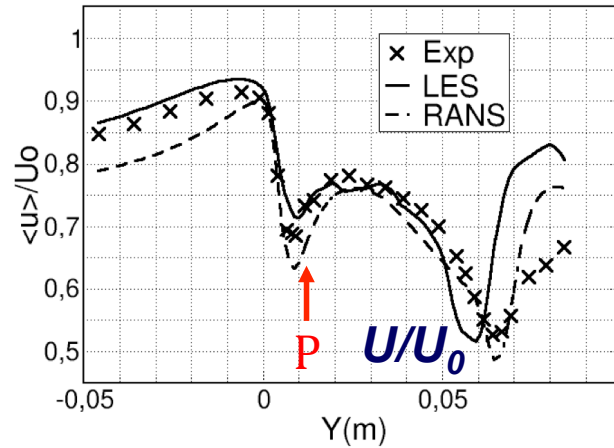


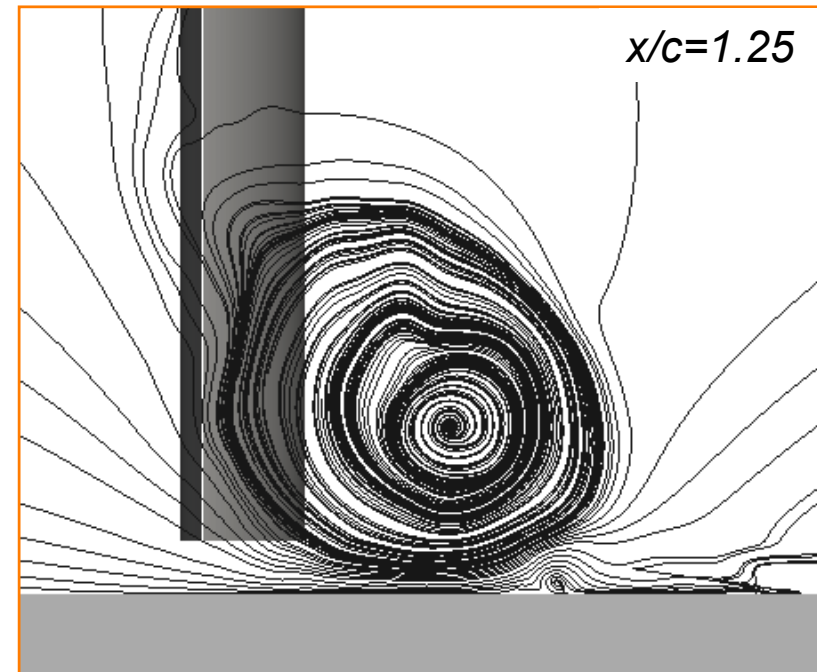
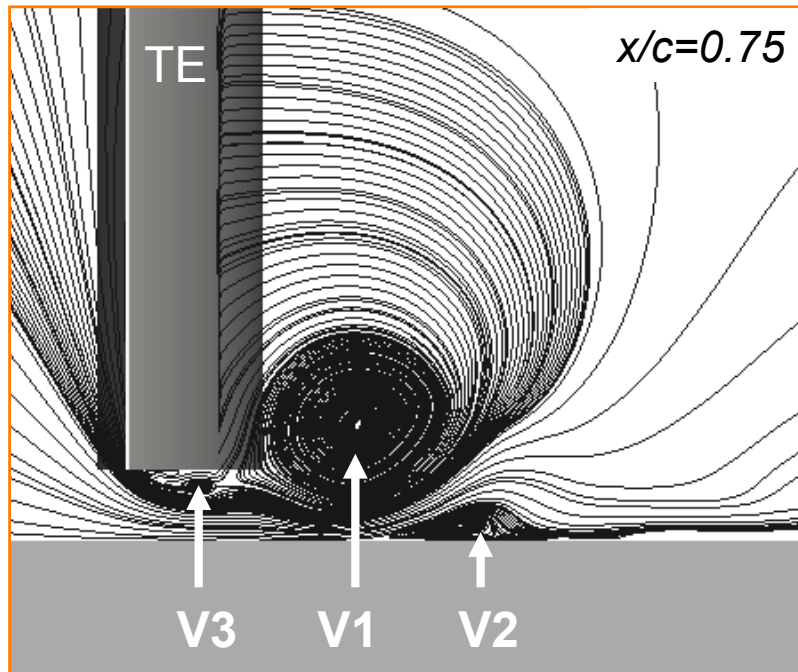
averaged



Iso-surface of Q-criterion (light grey, 10^8 s^{-1})
and streamlines (black)

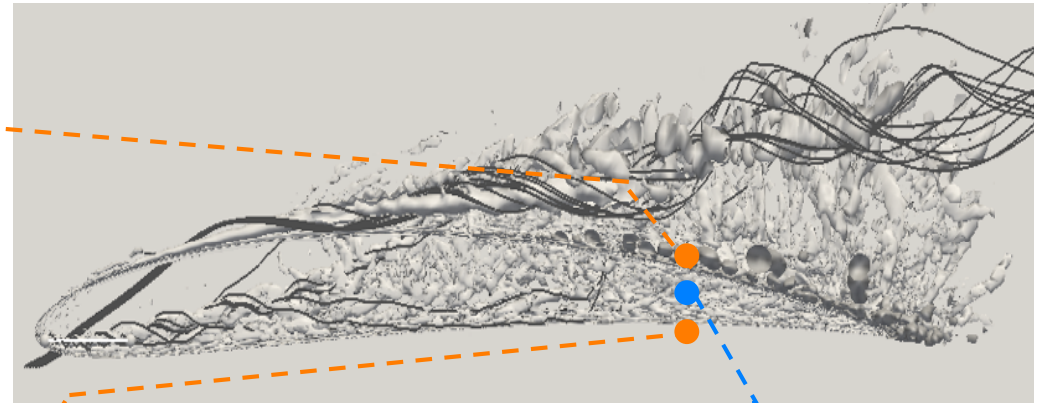
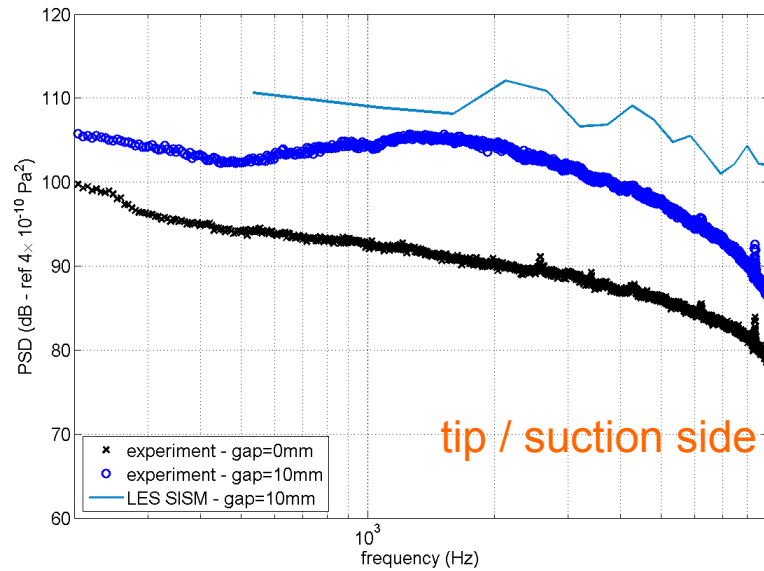
Tip-wake comparison ($x/c = 1.14$, $z/h = 0.5$)



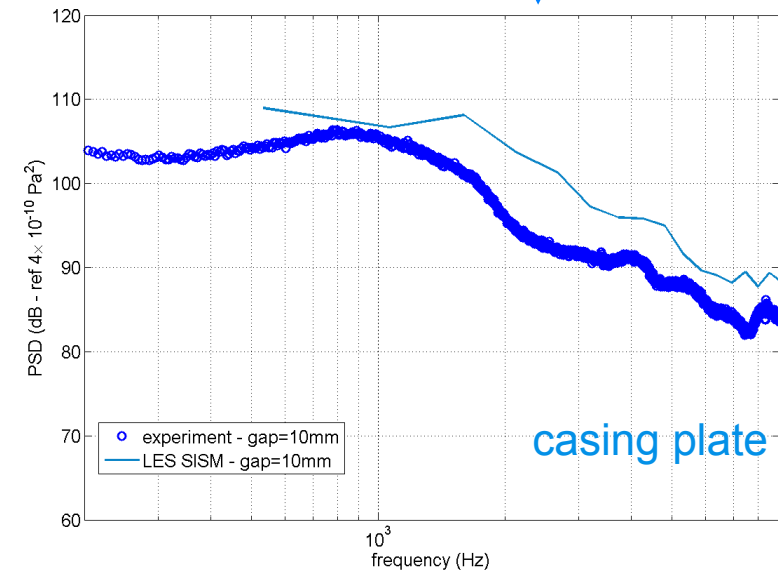
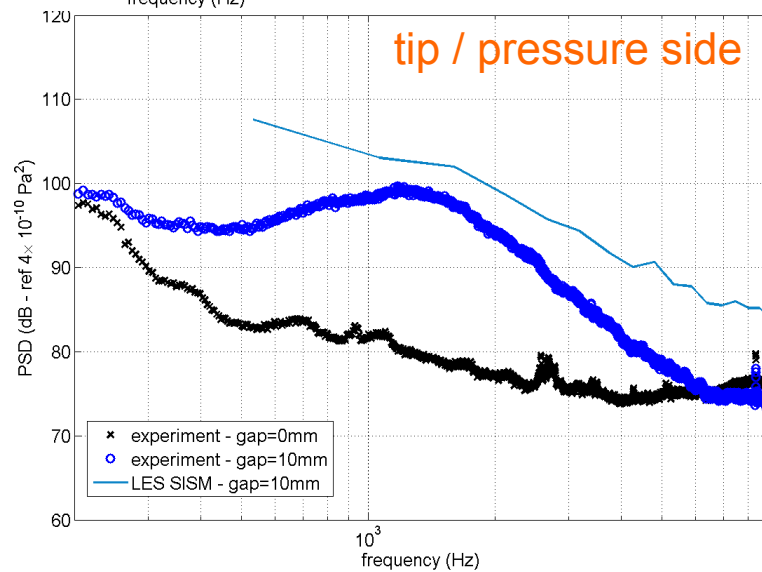


- The major structures are isolated for specific treatment by the SISM model
- V1: tip-leakage vortex, V2: counter-rotating vortex, V3: tip-separation vortex
- V3 previously shown to be associated with noise generation at trailing edge

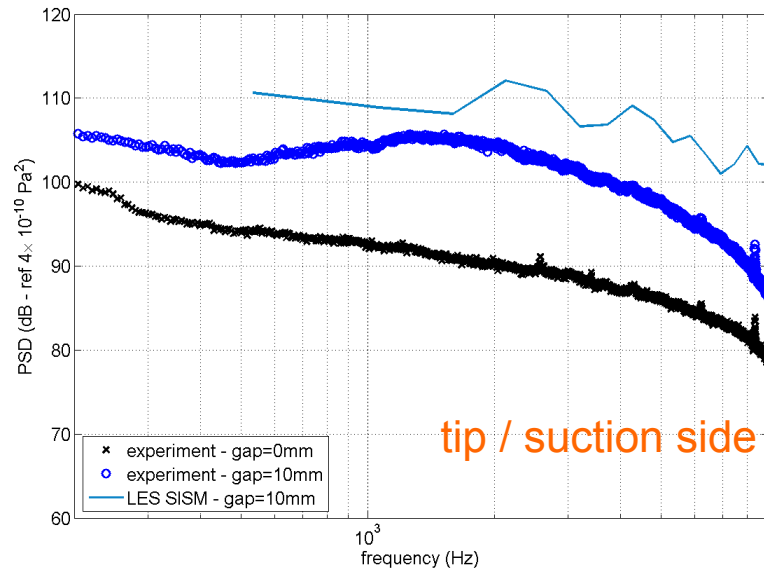
Wall-pressure spectra



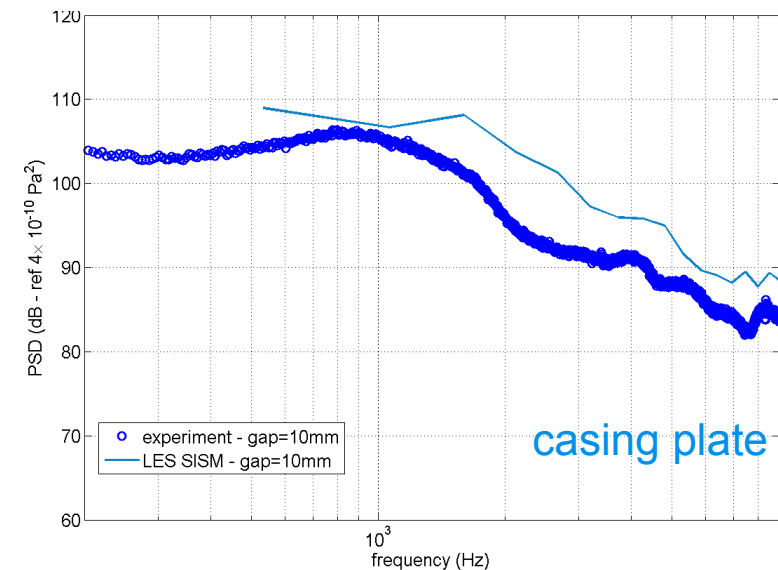
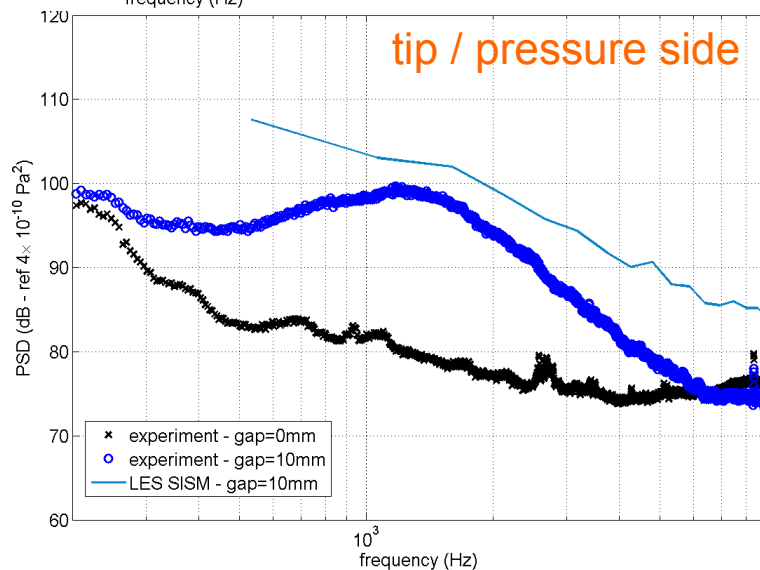
$\sim 3/4 c$



Wall-pressure spectra



- Gap => strong fluctuation increase.
- Spectral hump around 1kHz
- Rather good prediction of amplitudes and slopes by LES
- However, global overestimate, high freq

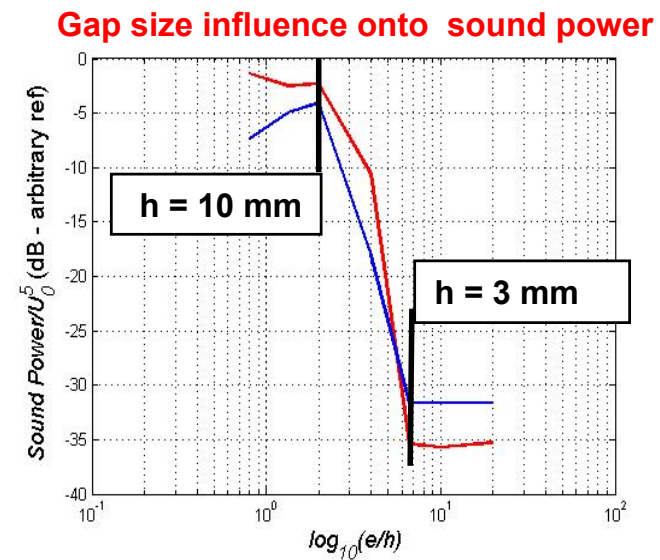
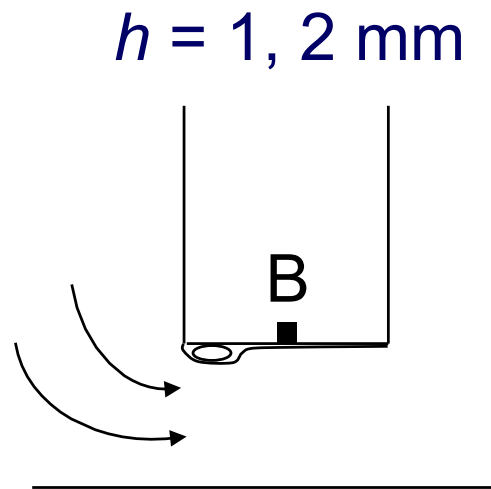


- **LES of a simplified tip-clearance configuration**
 - Very good prediction of the flow topology (tip edge C_p distribution, flow maps, velocity profiles..)
 - Casing-plate BL calibration would require turbulent inflow condition
 - However, influence of Casing TBL onto tip clearance flow is limited to the outer shear layer of the tip vortex
 - Quiet good prediction of the wall pressure spectra
 - The mean vortical structures are highlighted by specific treatment of the SISM subgrid-scale model
- **On-going & Future work**
 - Ffowcs-Williams & Hawkings prediction of the far-field
 - Investigation of Noise mechanisms by joint LES/far-field analysis
 - Inlet orcing

Конец

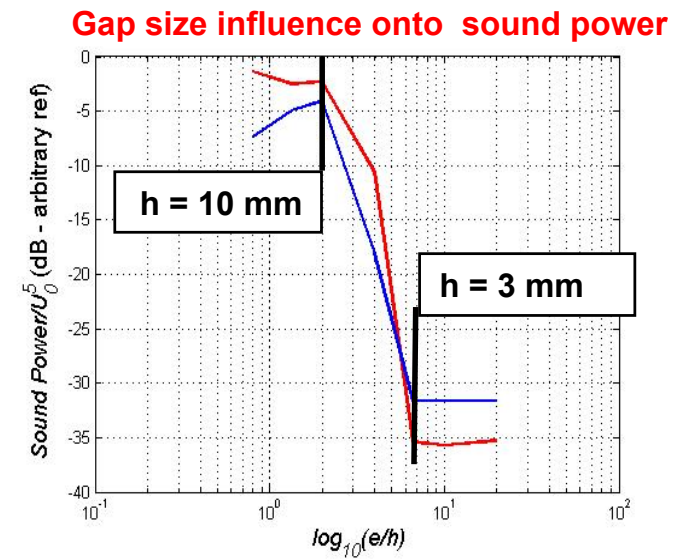
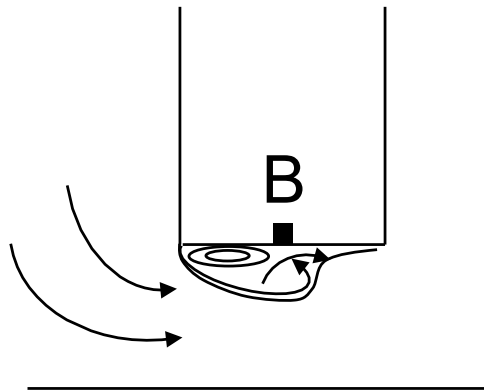
Спасибо !

Gap dependent Sound radiation



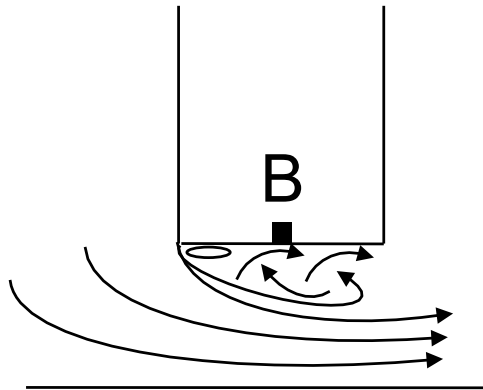
Gap dependent Sound radiation

$$10 > h \geq 3 \text{ mm}$$



Gap dependent Sound radiation

$h > 10 \text{ mm}$



Gap size influence onto sound power

