PROBAND: Improvement of Fan Broadband Noise Prediction: Experimental investigation and computational modelling

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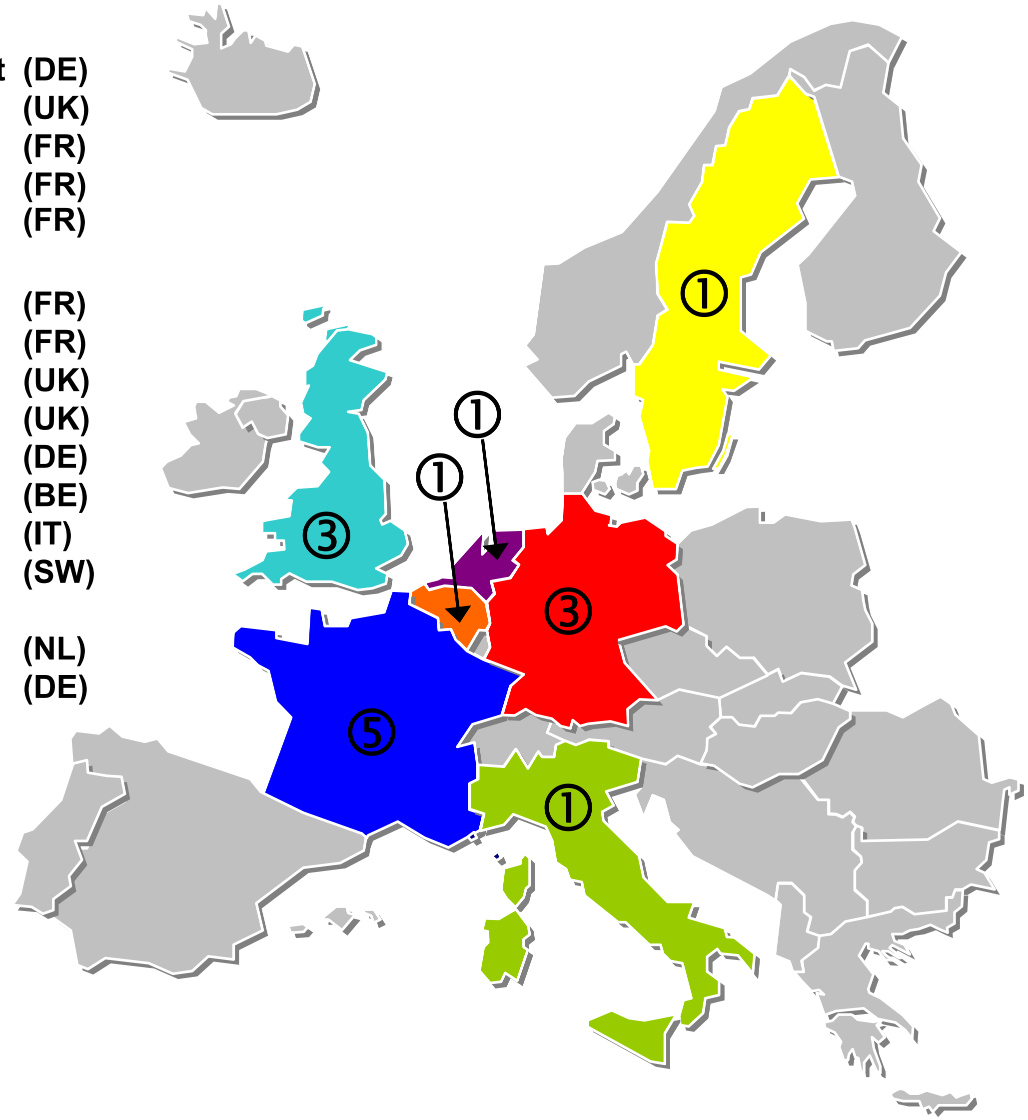
- Selected Final Results -

Lars Enghardt, DLR Berlin
Project Coordinator

EU FP6, Call 2, STREP PROBAND

<u>Consortium:</u>

DLR - Deutsches Zentrum für Luft und Raumfahrt	**(DE)**
RR - Rolls-Royce plc	**(UK)**
SnM - Snecma Moteurs	**(FR)**
ECL - Ecole Centrale de Lyon	**(FR)**
Flu - Fluorem SAS	**(FR)**
ONERA - Office National d'Études et Recherches Aérospatiales	**(FR)**
UPMC - Université Pierre et Marie Curie	**(FR)**
ISVR - Institute of Sound and Vibration Research	**(UK)**
UCAM - University of Cambridge	**(UK)**
TUB - Technische Universität Berlin	**(DE)**
VKI - Von Karman Institute	**(BE)**
UR3 - Università Roma Tre	**(IT)**
KTH - Kungliga Tekniska Högskolan	**(SW)**
NLR - Nationaal Lucht- en Ruimtevaart Laboratorium	**(NL)**
ACAT - Anecom Aerotest	**(DE)**



- **Budget: 5 M€**
- **Project start: 1. April 2005**
- **Duration: 3,75 years**

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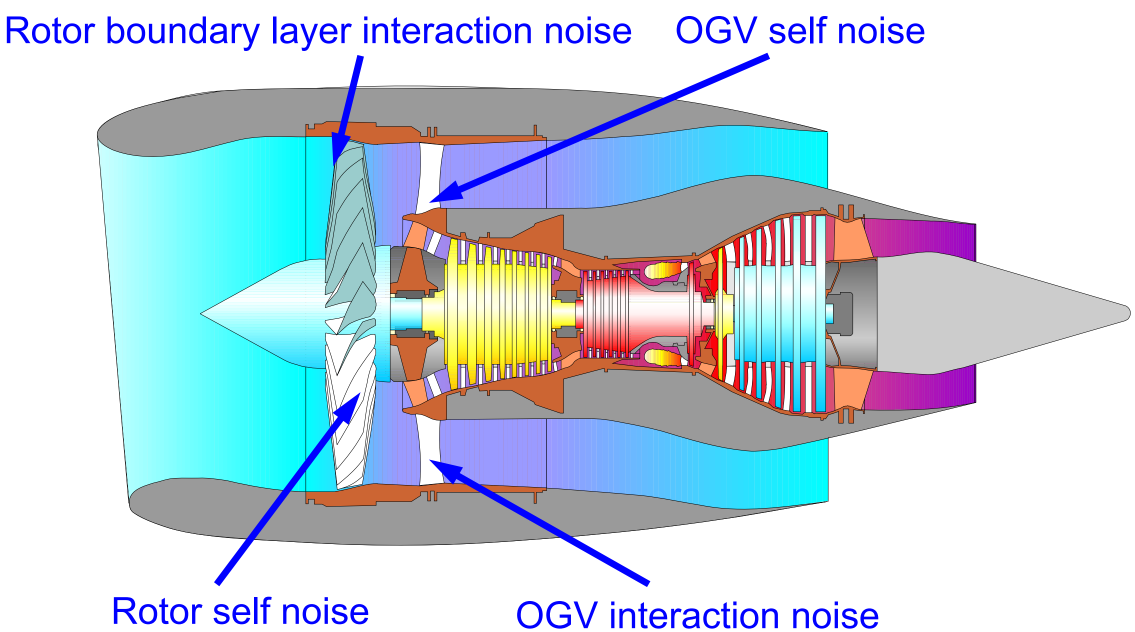
Motivation: Broadband Fan Noise Sources



Interaction mechanism between

- The blade-tip of the rotor fan and the turbulent boundary layer on the inlet-duct (rotor boundary layer interaction noise)
- Turbulent eddies convected in the rotor boundary layer and the rotor trailing edge (rotor self noise)
- The rotor wake and the downstream outlet guide vanes (OGV interaction noise)
- Turbulent eddies convected in the vane boundary layer and the vane trailing edge (OGV self noise)

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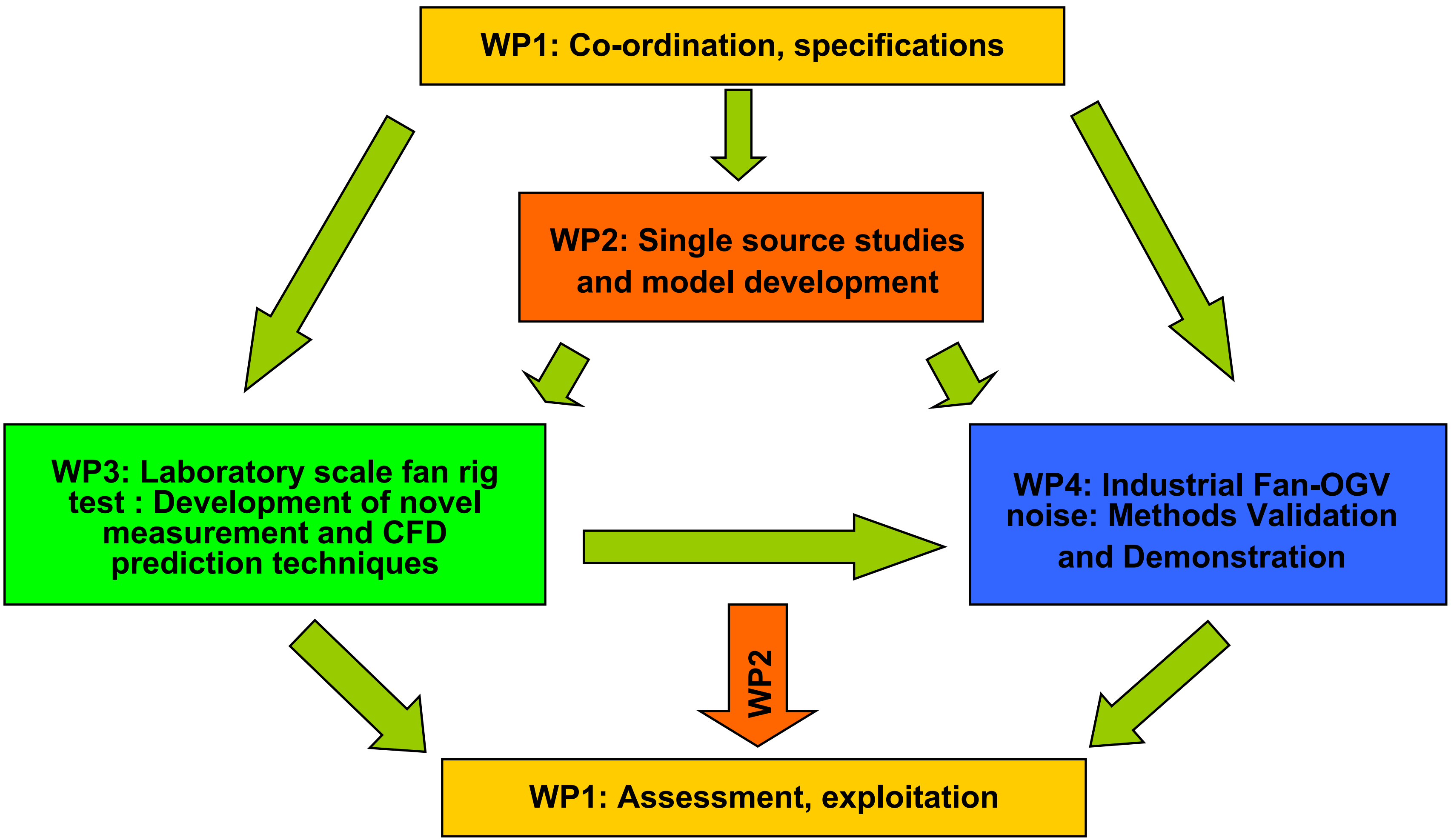
Project Structure



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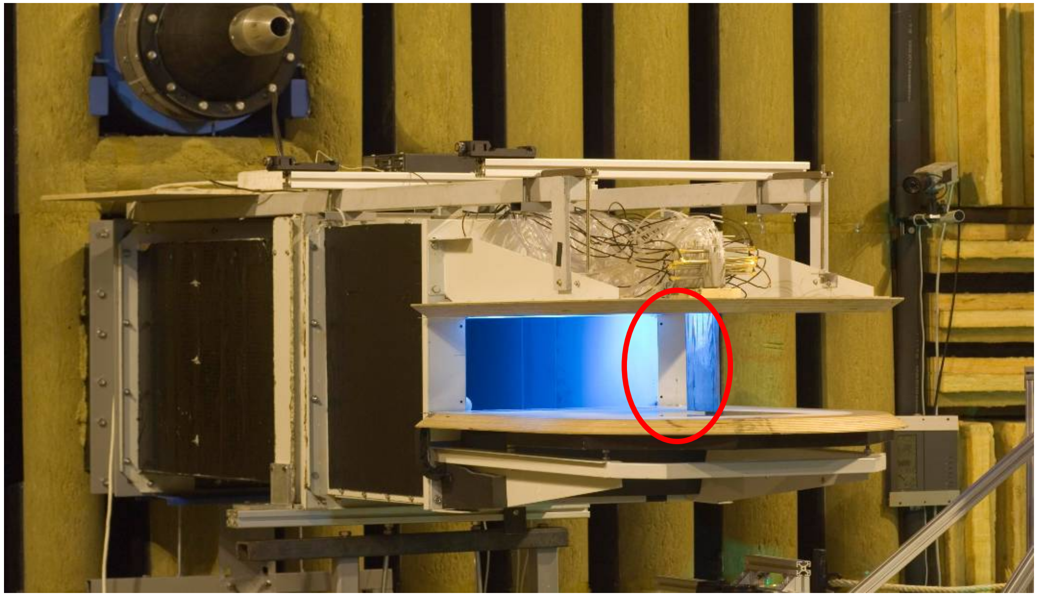
WP2: Single source studies and model development

Objective

- Develop and assess improved existing and future broadband noise prediction tools

Single Airfoil experiment (ECL)



- TE noise
- Tip/casing noise

Measurements

- PIV, LDA, HWA
- Wall pressure
- Far field
- Combined measurements

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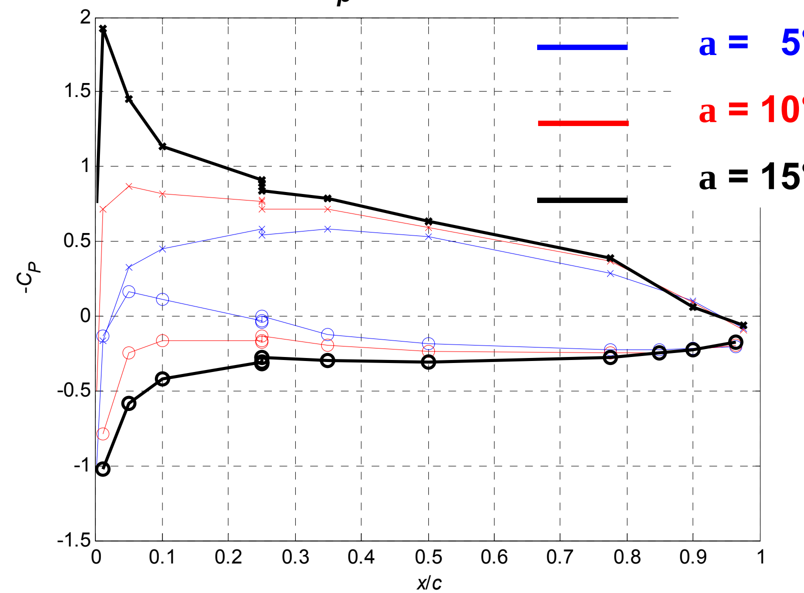
Features

- NACA5510: *c* =200 mm ; span: 200mm
- High lift: 5% camber and 15º *AoA*
- Gap: *h*~ 10 mm= 5% c
- U_0= 70 m/s (M~0.2; Re_c~9.3 10^5)
- Low turbulence inflow (0.7%)
- Incoming TBL: *d*~ 1.8*h (99% thickness)*

Variations of parameters: U_0 , *AoA* and *h*

C_p at mid span

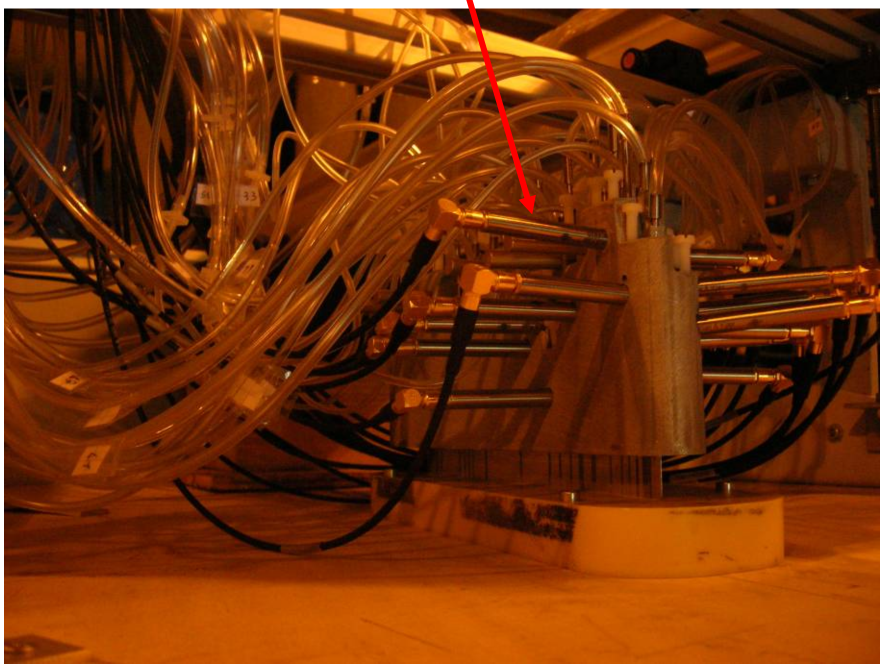


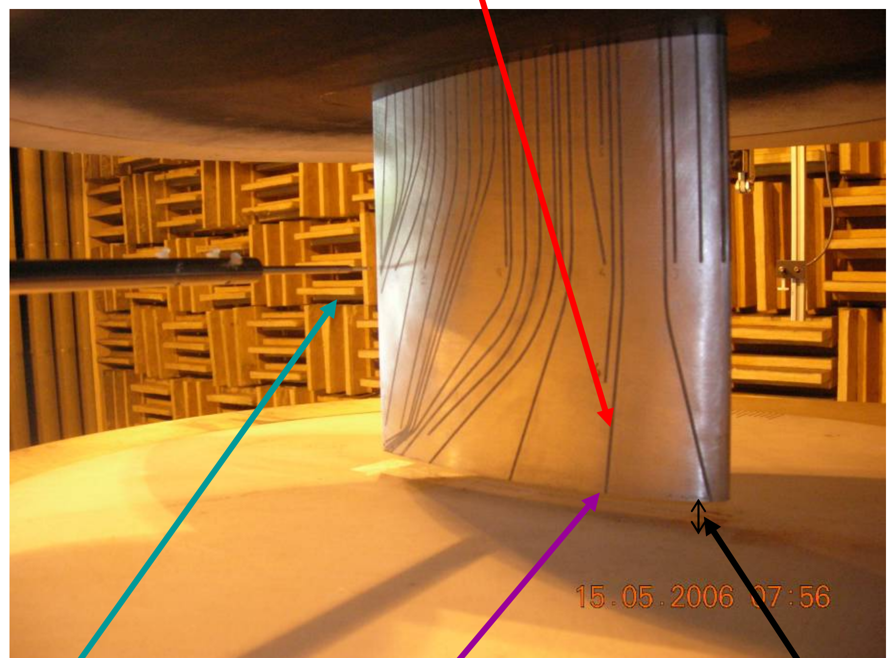
Single Airfoil experiment, unsteady pressure measurements (ECL)

Implementation

B& K “low cost” ICP -microphones

Pressure tube





HW probe

Pin hole

Gap

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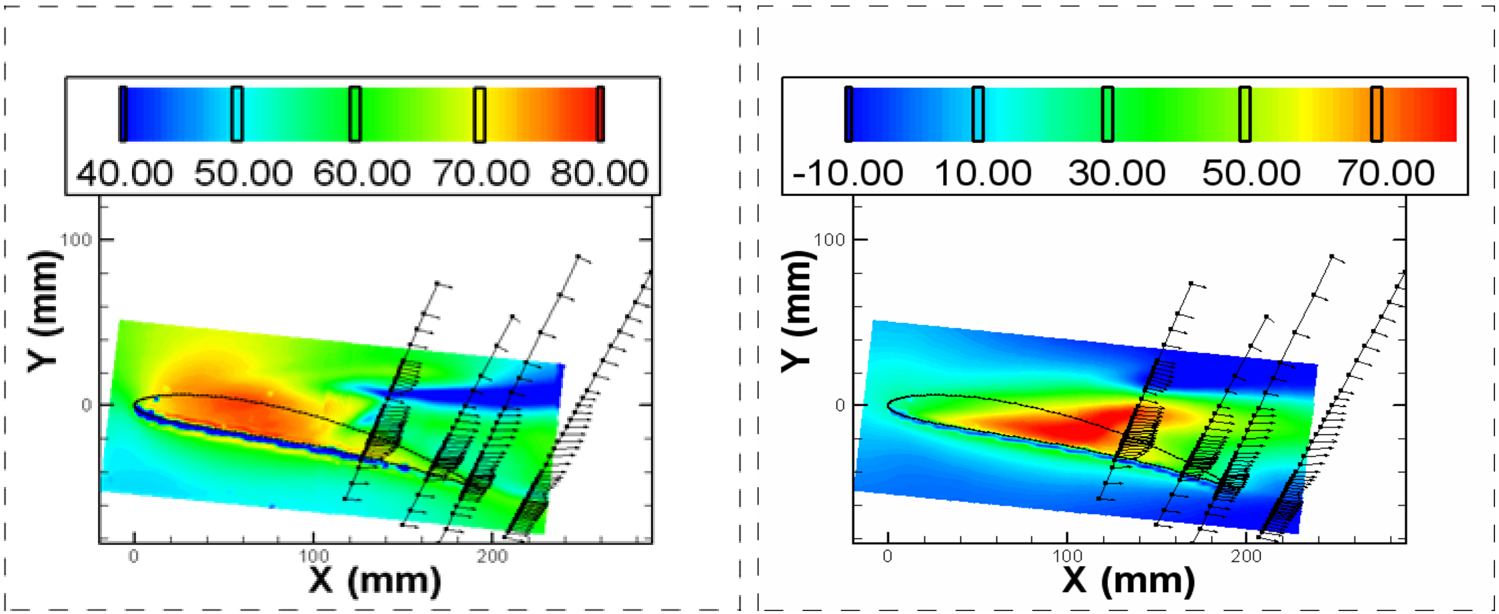
Single Airfoil experiment, PIV and HWA (ECL)

Steady Flow in gap region : mid-gap section

U_0 = 70 m/s ; a= 15° ; h= 10 mm ;



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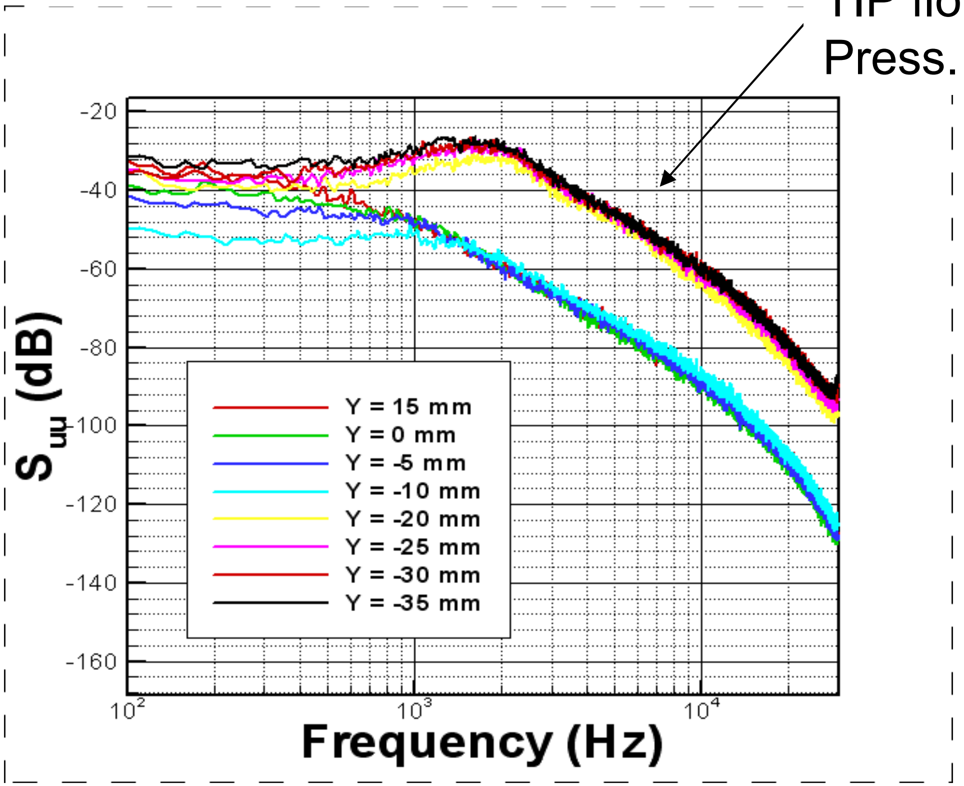
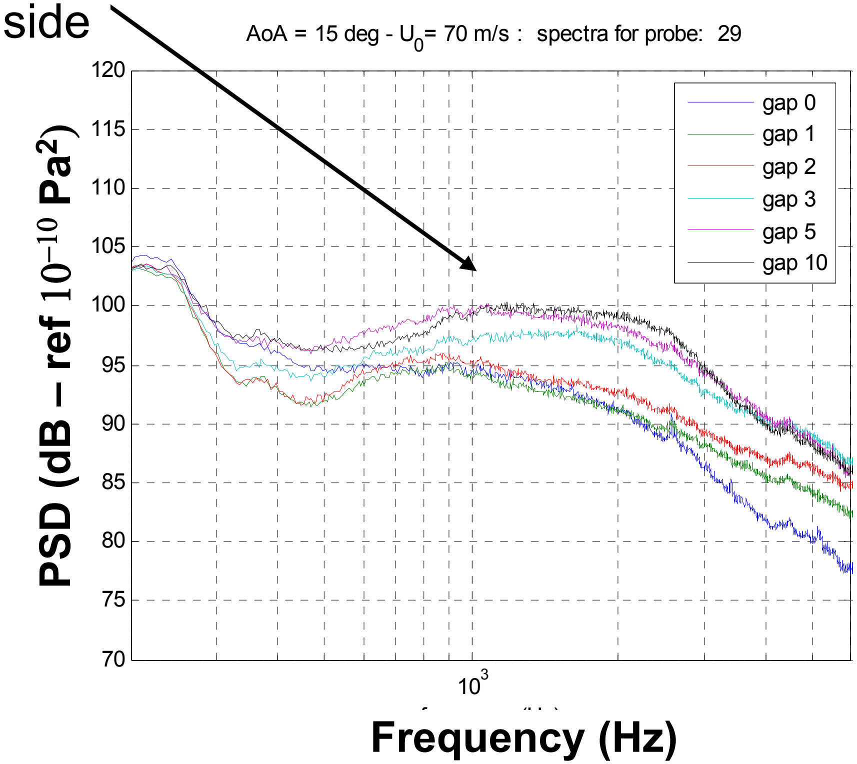
Single Airfoil experiment, unsteady velocity/pressure spectra (ECL)

Velocity spectra (HWA); gap=10 mm
***x/c*=0.95 ; mid gap**



TIP flow
Press. side

pressure spectra
***x/c*=0.95 ; 1.5 mm from tip**



Hump between 1 and 3 kHz and global amplification above 500 Hz

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BBN modeling: TE noise model (ECL)

- Mechanism: Pressure perturbations are scattered as acoustic waves at the TE
- The far-field sound pressure PSD is related to the wall-pressure statistics closely upstream of the trailing-edge
- For a large aspect ratio airfoil, this relation comes down to

$$S_{pp}\left(\vec{x},\omega\right) = \left(\frac{\omega c x_3}{4\pi c_0 S_0^2}\right)^2 \frac{L}{2} \left|\mathcal{L}\left(\frac{\omega}{U_c},\frac{\bar{k}x_2}{S_0}\right)\right|^2 \Phi_{pp}(\omega) l_y \left(\omega,\frac{\bar{k}x_2}{S_0}\right)$$

Input from exp. and/or CFD

Analytical response function

Convection speed

Wall-pressure spec.

Spanwise coherence scale

New: Wall pressure spectrum can be inferred from RANS computed TBL properties [Rozenberg et al (2008)]

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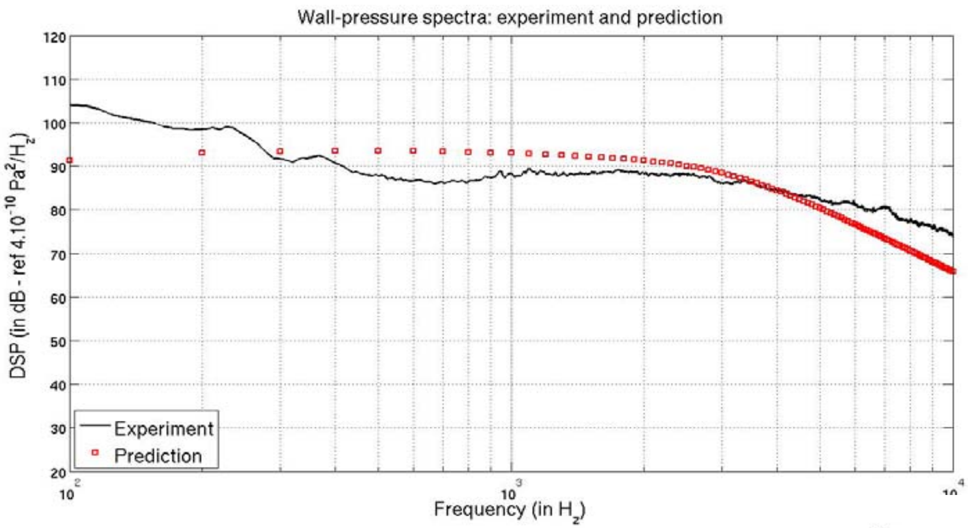
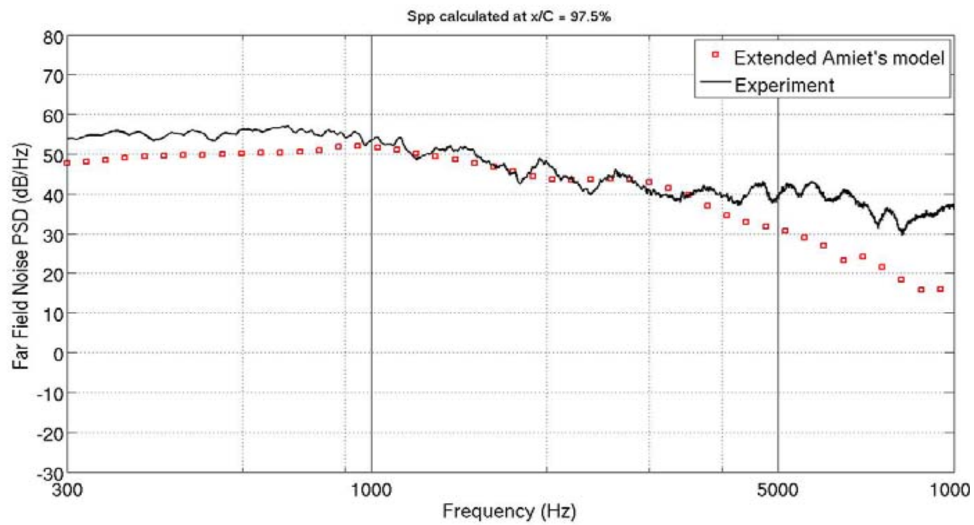
BBN modeling: Application (ECL)

Wall pressure spec. predicted from RANS



TE model

Exp. data: Far field



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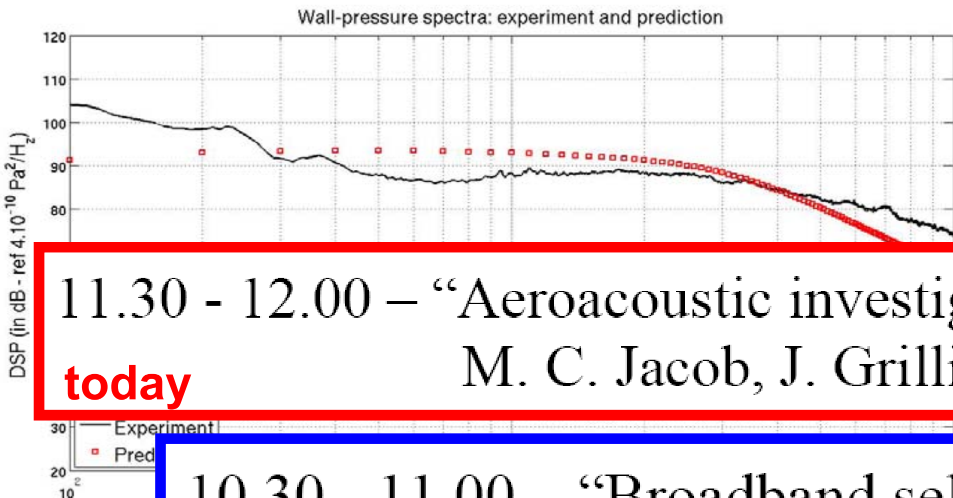
BBN modeling: Application (ECL)

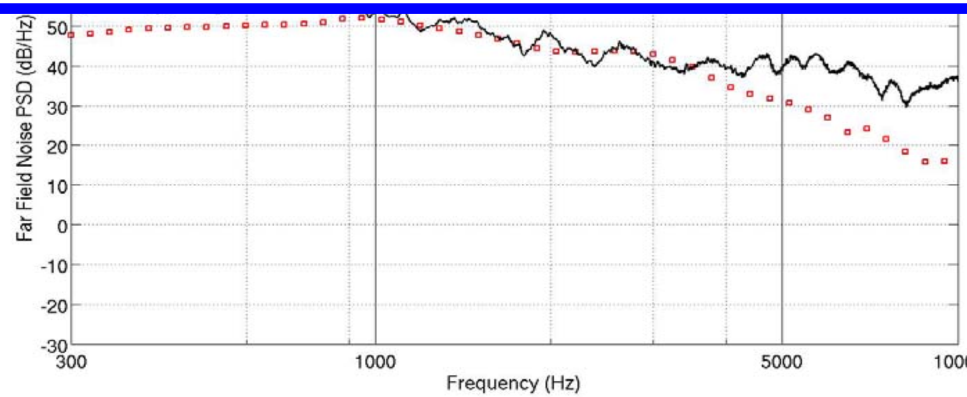
Wall pressure spec. predicted from RANS



TE model

today 11.30 - 12.00 – "Aeroacoustic investigation of a single airfoil tip leakage flow"
M. C. Jacob, J. Grilliat, R. Camussi and G. Caputi Gennaro

tomorrow 10.30 - 11.00 – "Broadband self noise prediction using RANS data"
J. Grilliat, M. C. Jacob, J. Boudet, M. Roger



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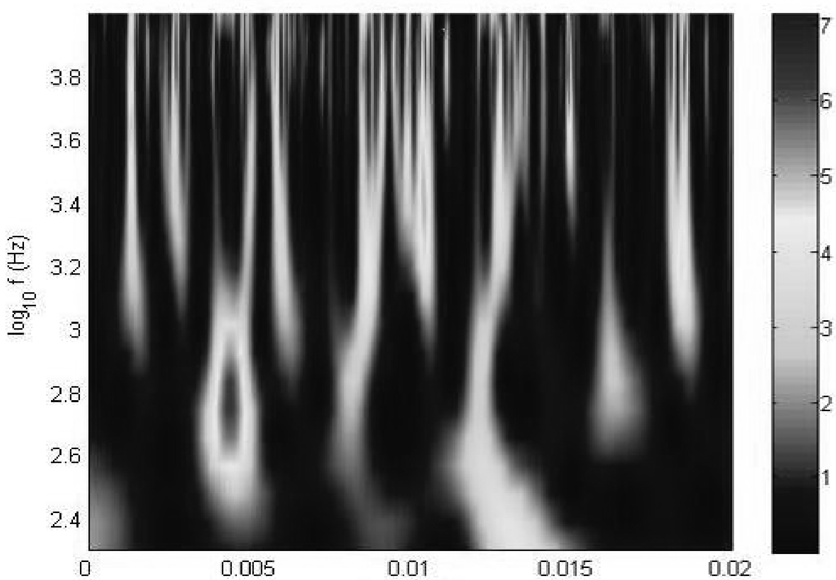
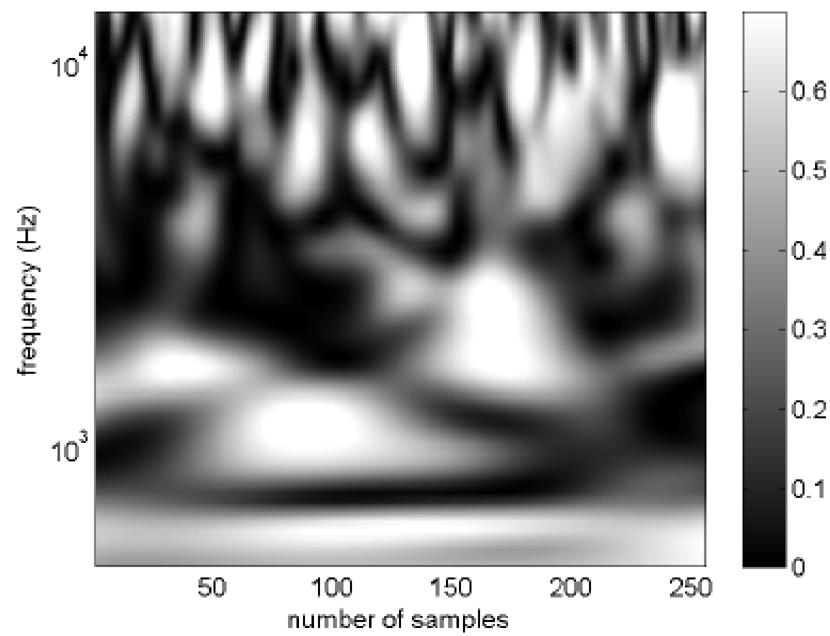
Wavelet analysis of pressure fluctuations (UR3, ECL)

Conditional statistics of pressure or velocity based on localized pressure events extracted using wavelet indicators



Local Intermittency Measure: equivalent to a 2D representation of the Fourier auto-spectrum

(Camussi et al., AIAA 2007-3685, Grilliat et al., AIAA 2008-2845)



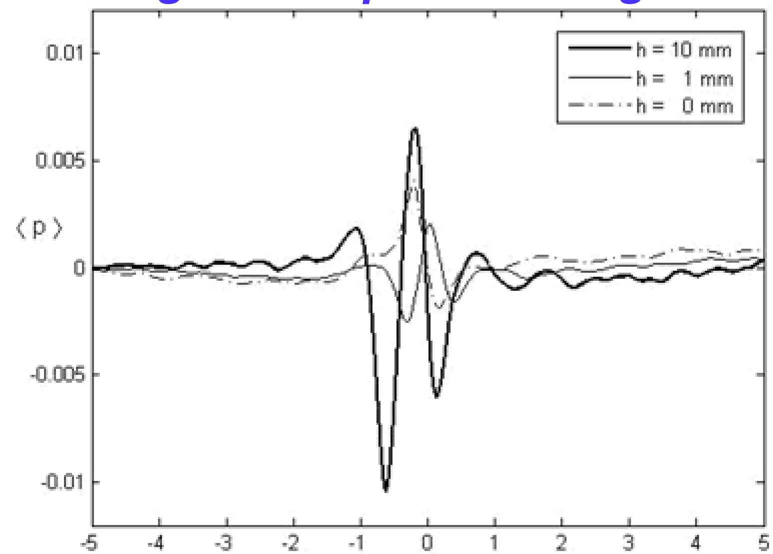
Cross-Wavelet: equivalent to a 2D representation of the Fourier cross-spectrum

(Camussi et al., JFM 2008)

Averaged signatures (UR3, ECL)

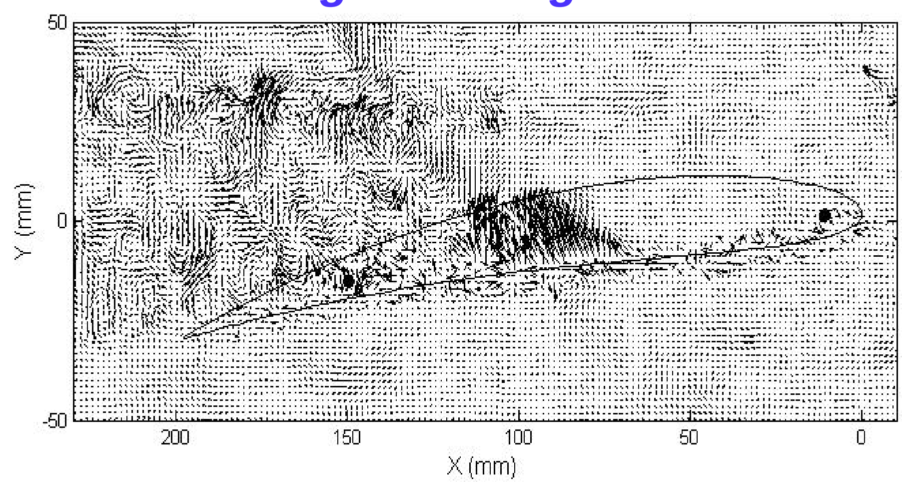
- Oscillations are due to the gap
- Event duration scales with $U_0^{1/2}$
- Potential point-vortex model: pressure induced by co-rotating vortices

Averaged wall-pressure signatures



- Events are originated at about 50-60% the chord length
- Results confirmed from the far-field pressure conditioning: noise source?

Averaged PIV signatures



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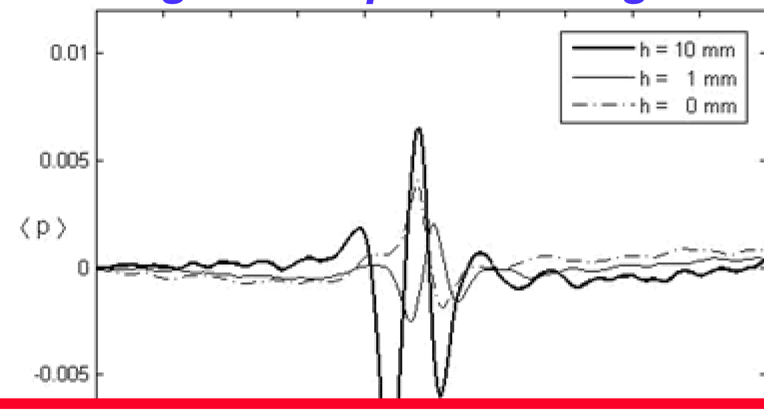
Averaged signatures (UR3, ECL)

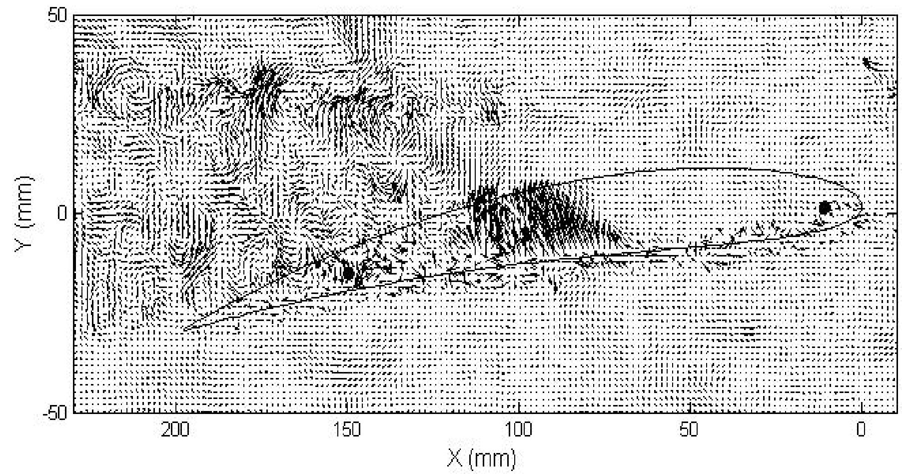
Averaged wall-pressure signatures



- **Oscillations are due to the gap**
- **Event duration scales with $U_0^{1/2}$**
- **Potential point-vortex model: pressure induced by co-rotating**

10.00 - 10.30 – “Pressure velocity conditional statistics in a tip leakage flow “
R. Camussi, G. Caputi Gennaro, M.C. Jacob, J. Grillat **today**

Averaged PIV signatures



- **Events are originated at about 50-60% the chord length**
- **Results confirmed from the far-field pressure conditioning: noise source?**

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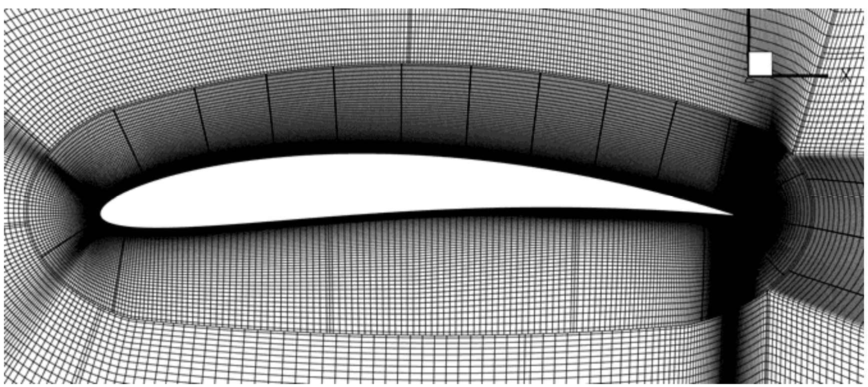
EU Framework 6 Research

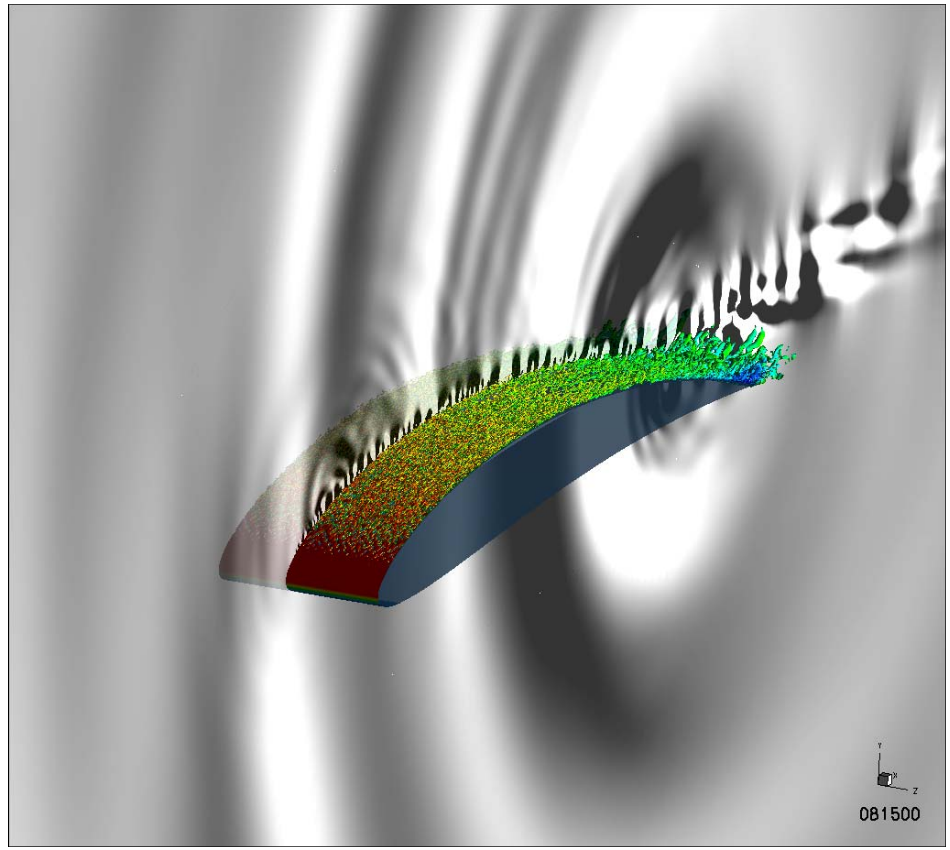
CFD on Selfnoise (TUB)

- **Simulation of boundary layer broadband noise with IDDES**
  - grid: 5.3 million cells
    - 40 cells in span wise
  - span wise extent 1cm (d/c = 0.05)
  - LES like grid on suction side
    - dx = 2*dz = 0.5 mm
  - coarser grid on pressure side

Grid slice



Vortex structures colored with velocity magnitude (λ_2), on slice: visualization of radiated sound (dp/dt)



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EU Framework 6 Research

CFD on Selfnoise (TUB)

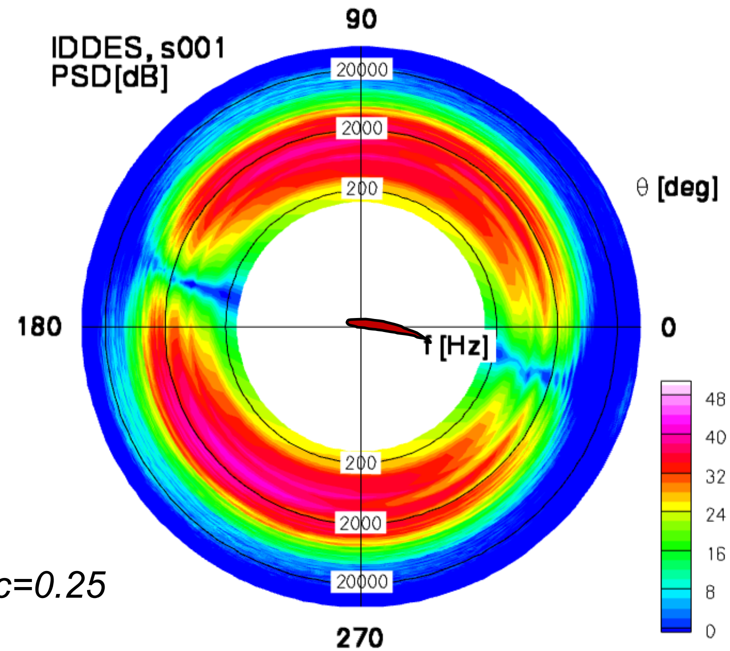
- **Simulation of boundary layer broadband noise with IDDES**

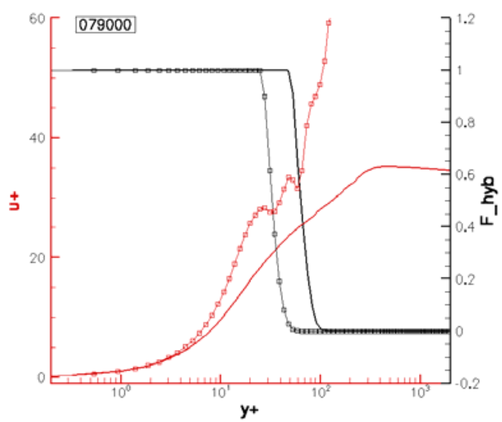
→ Simulation shows fully attached resolved boundary layer
  - RANS/LES blending inside turbulent boundary layer

→ Interaction of turbulent boundary structures with TE generates broadband noise in the far field

→ broadband noise directivity shows typical dipol directivity

broadband noise directivity in dB from 100 Hz to 30 kHz





Boundary layer analysis at x/c=0.25
red: u^+- y^+ plot
black: blending function RANS/LES
(lines – averaged, symbols - instanteneous)

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EU Framework 6 Research

CFD on Selfnoise (TUB)

- **Simulation of boundary layer broadband noise with IDDES**

→ Simulation shows fully attached resolved boundary layer

  – RANS/LES blending inside turbulent boundary layer

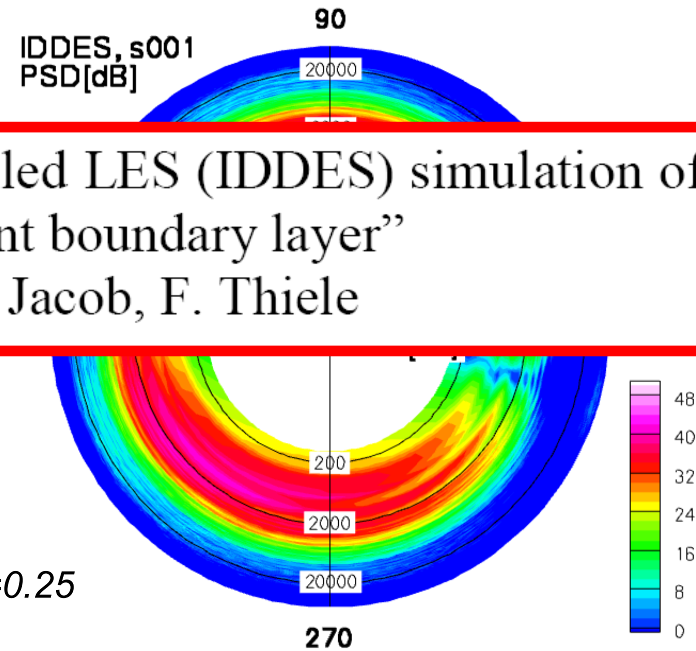
→ Interaction of turbulent boundary structures

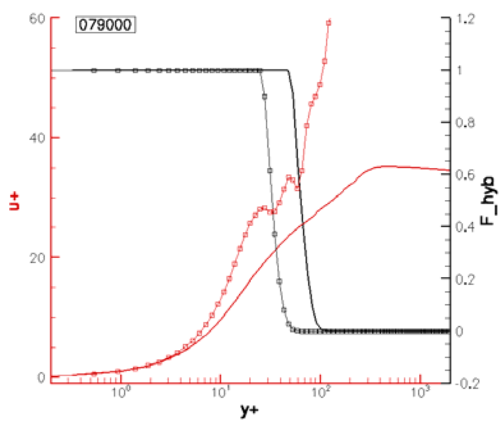
18.45 - 19.15 – "Measurements and wall modelled LES (IDDES) simulation of trailing edge noise caused by a turbulent boundary layer"
B. Greschner, J. Grilliat, M. C. Jacob, F. Thiele

today

dipol directivity

broadband noise directivity in dB from 100 Hz to 30 kHz





Boundary layer analysis at x/c=0.25
red: u^+- y^+ plot
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(lines – averaged, symbols - instanteneous)

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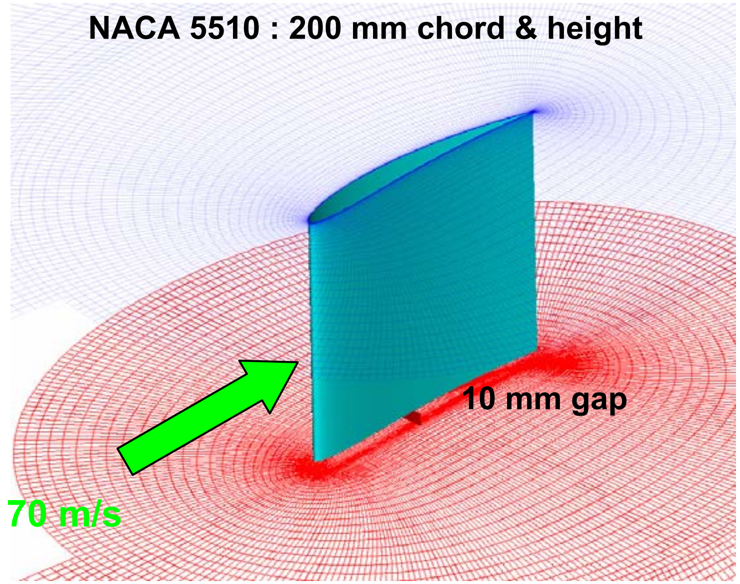
LES of a Fan-Tip with gap: characteristics (FLU)

- **Single airfoil configuration with gap, representative of an engine fan-tip / turbulent boundary layer interaction, generator of broadband noise**
- **3D N.S. compressible simulation realized at Fluorem with Turb'Flow®**



- ≈ 3 000 000 grid nodes
- Multiblock structured finite volume
- Jameson centered spatial scheme 4^{th} order
- Explicit 3 steps Runge Kutta of Wray time marching, $\Delta t = 2\ 10^{-9}$ s
- LES filtered structure function turbulence model (following Ducros, Comte and Lesieur)
- Computations realized on 16 CPU cores (AMD Opteron® @2400 Mhz)

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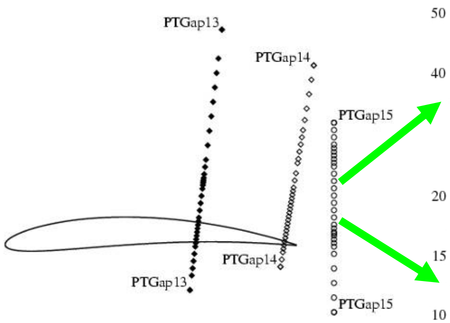
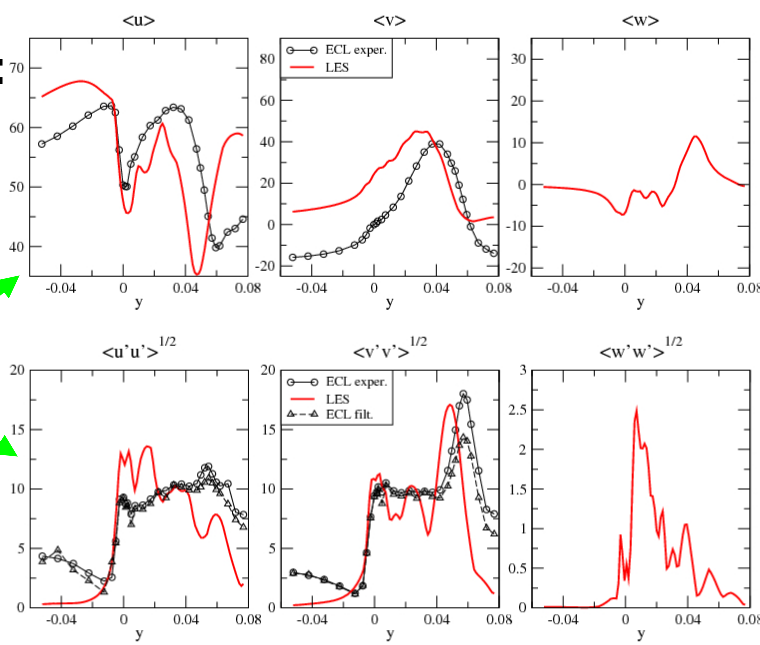
LES of a Fan-Tip with gap: aerodynamics (FLU)

- A fully unsteady configuration
- Time-averaging of aerodynamic fields
- Large tip-vortex flow interaction with incoming boundary layer + TE vortex shedding: associated to broadband noise sources

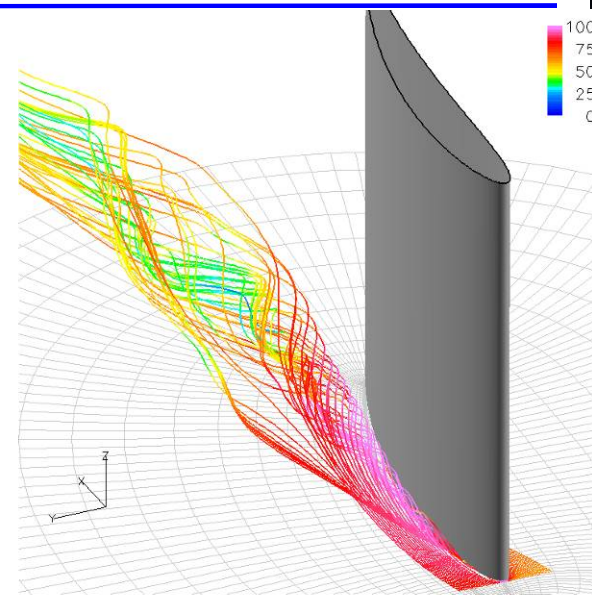
Velocity profiles :
Mean and ...

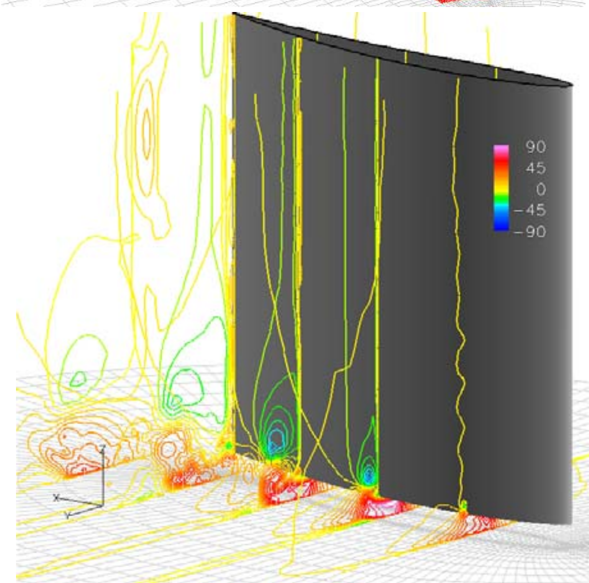




... fluctuations
(e.g. Ptgap15)

Flow structure : The tip vortex flow





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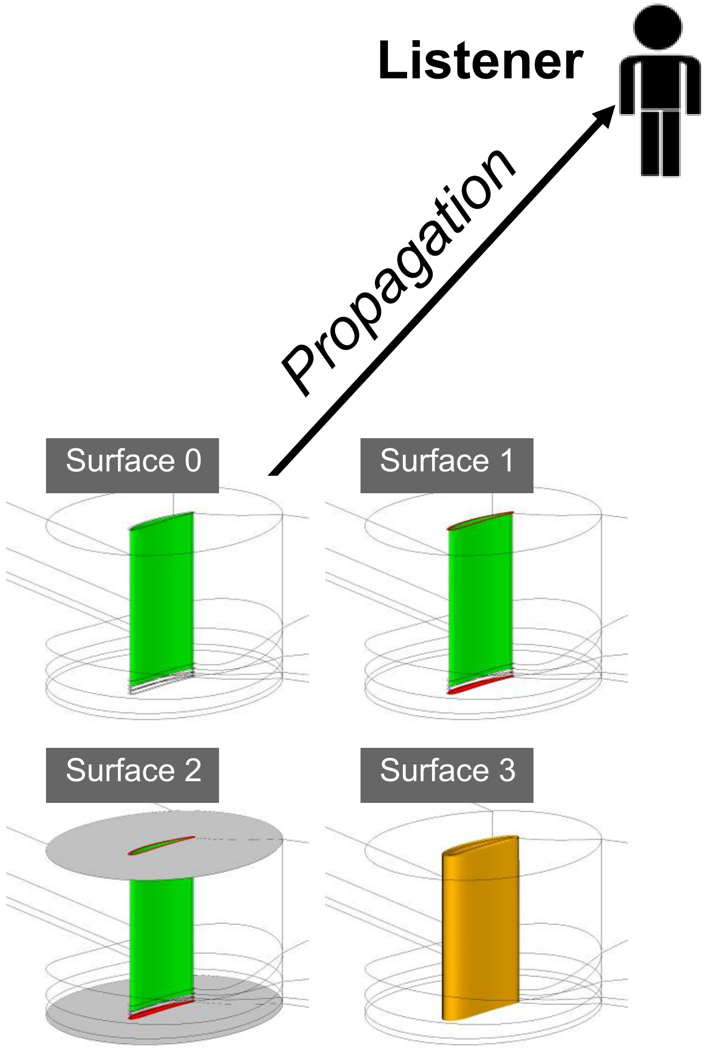
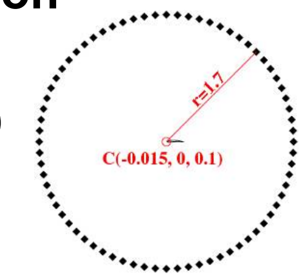
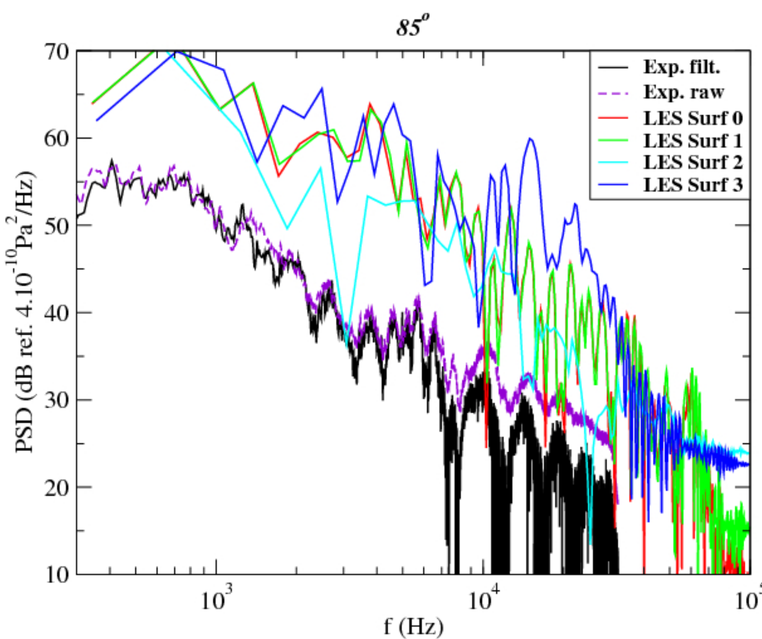
LES of a Fan-Tip with gap: acoustics (FLU)



Different integration surfaces

- **Ffowcs Williams and Hawkings (FWH) acoustic analogy associated with a retarded time formulation**
- **FWH pressure surfaces time series, recorded during LES computation**
  - **Observers placed on a 2D circle**
  - **Example :**





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WP3: Laboratory scale fan rig test : Development of novel measurement and CFD prediction techniques

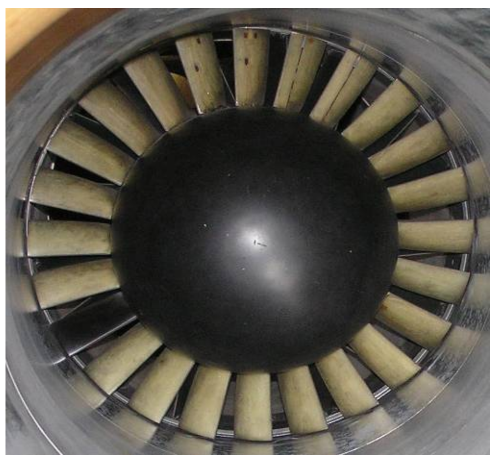
- **Objectives**
  - provide a parametric study on broadband noise sources in a laboratory-scale fan rig
  - develop advanced measurement techniques on this fan rig
  - evaluate the predictions of the broadband noise of the laboratory fan rig using the RANS/semi-analytic methods and validated LES/DES models

Setup of laboratory scale experiment (DLR)

Low speed scale fan rig (DLR Berlin)

D	= 0.5 m
M_{tip}	= 0.22
Re	= 220 000

24-blade rotor



16-vane stator

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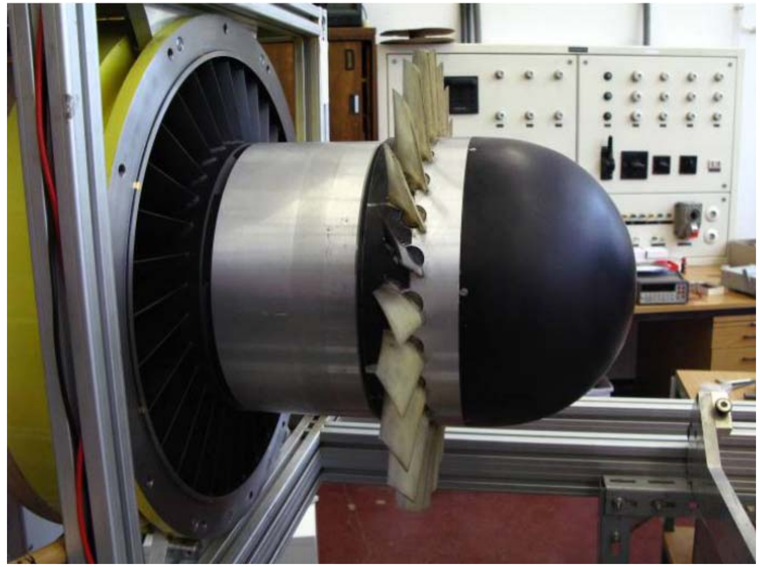
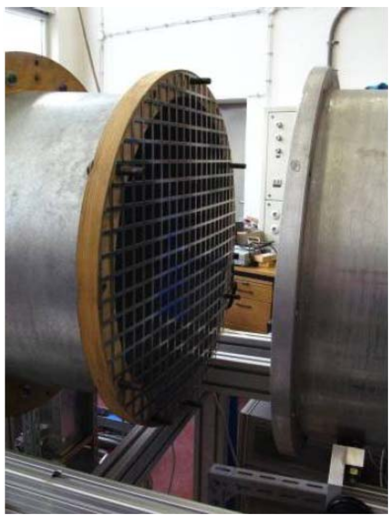
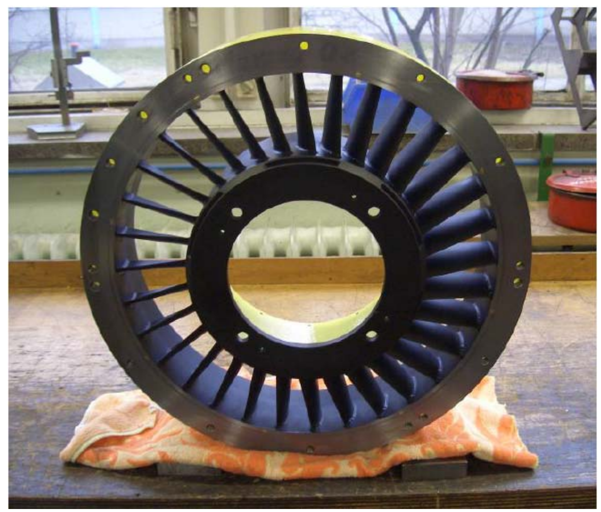
Setup of laboratory scale experiment (DLR)

Rotor shaft extension to increase rotor-stator gap



Grid for increased inflow turbulence





32-vane stator

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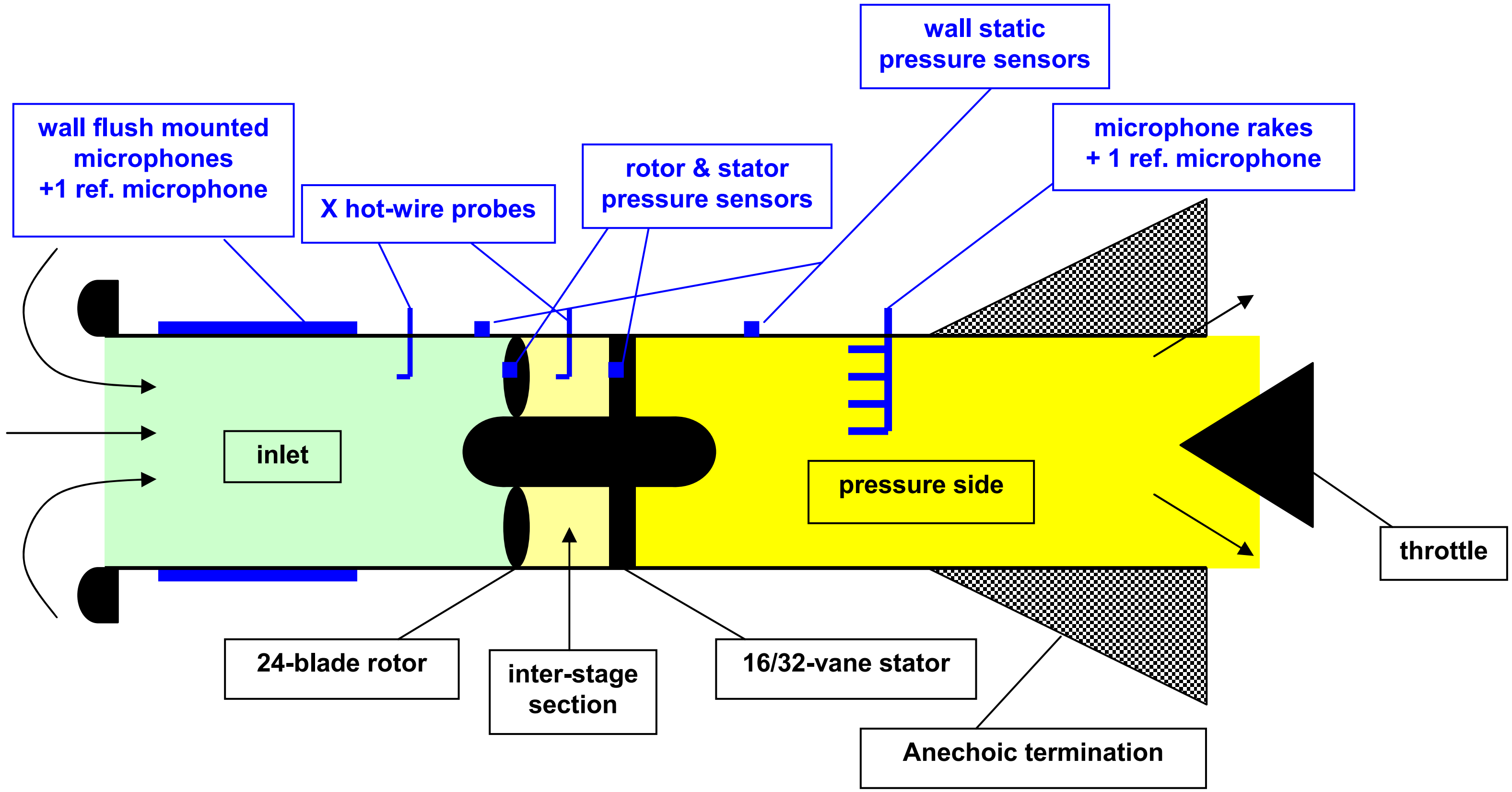
Setup of laboratory scale experiment (DLR)



- performance measurements
- hot-wire velocity measurements
- acoustic measurements
- blade unsteady pressure measurements

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Experimental result: Effect of fan speed (DLR)

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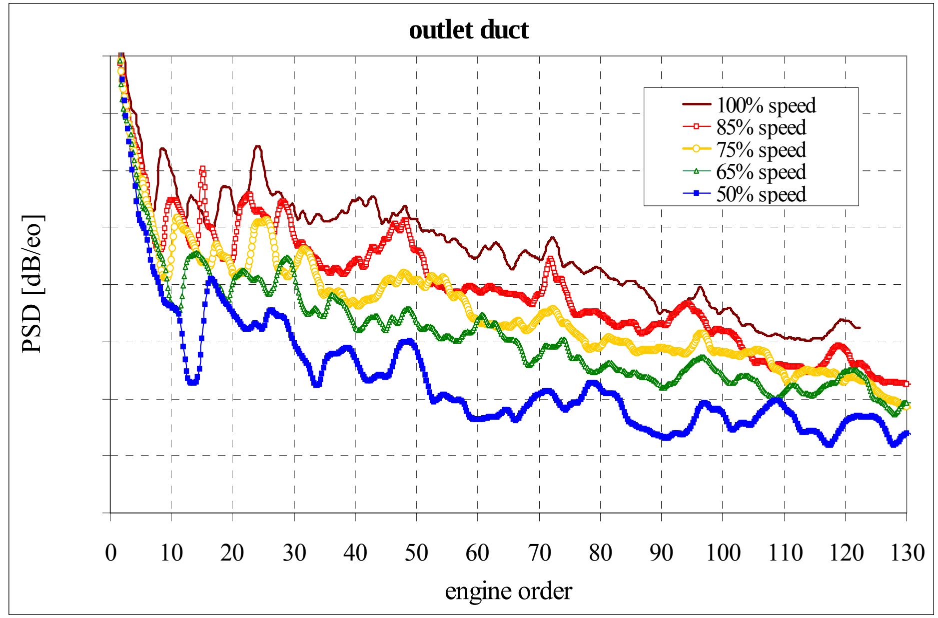
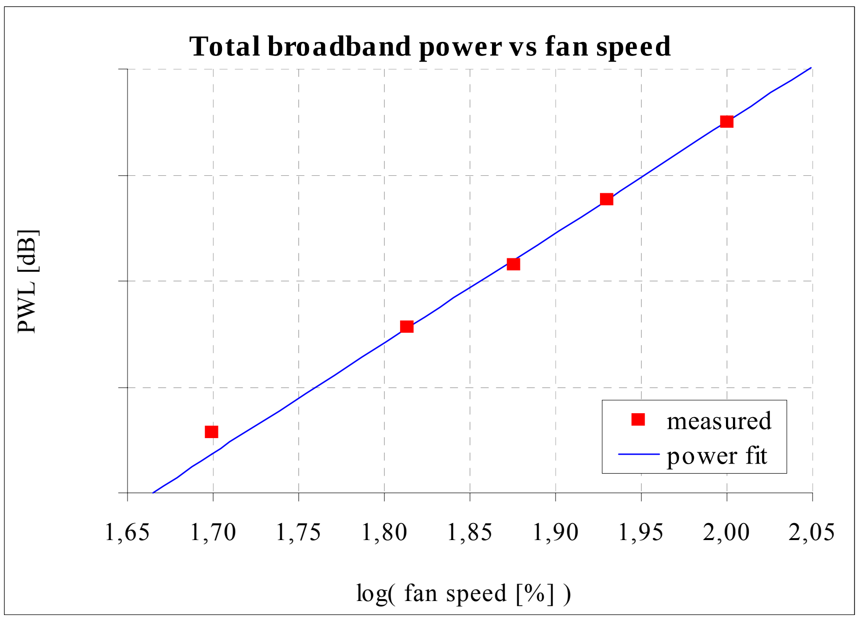
Effects on acoustic spectra:

- Max. levels near Blade Passing Frequency
- Nearly constant decay
- Increasing levels with increasing speed





$$P_{BBN} \propto U_{tip}^{5.2}$$

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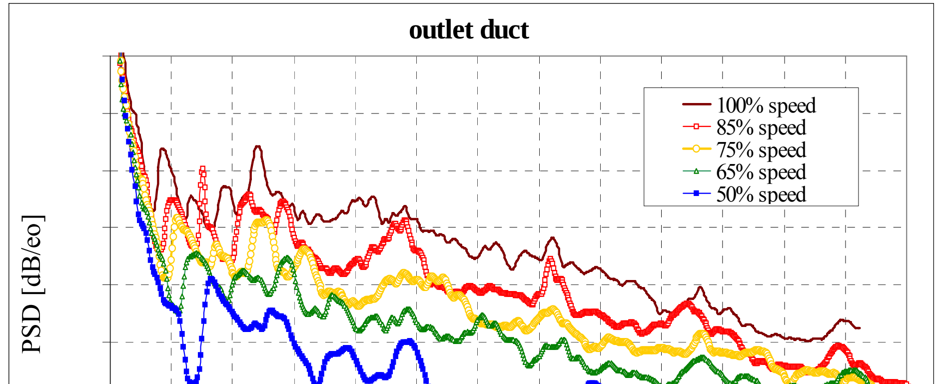
Experimental result: Effect of fan speed (DLR)

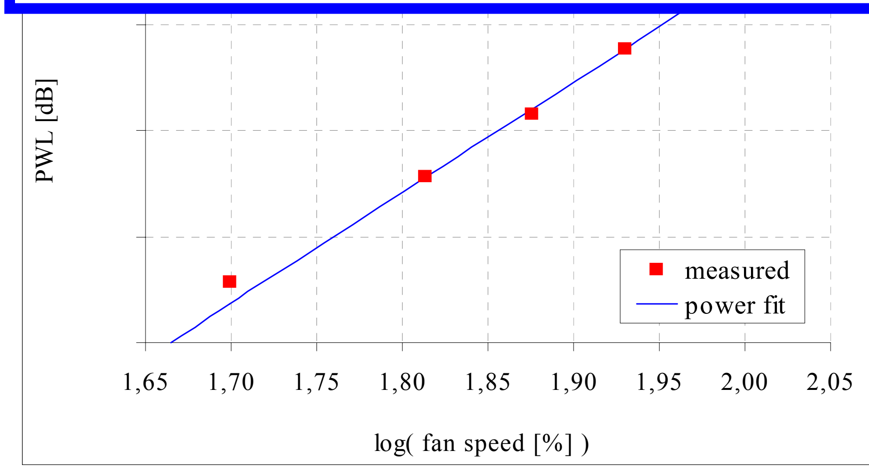
Effects on acoustic spectra:

- Max. levels near Blade Passing Frequency
- Nearly constant decay
- Increasing levels with increasing speed



13.00 - 13.30 – "Parametric study on the broadband noise generated by a low-speed fan"
A. Moreau, L. Enghardt

tomorrow



$$P_{BBN} \propto U_{tip}^{5.2}$$

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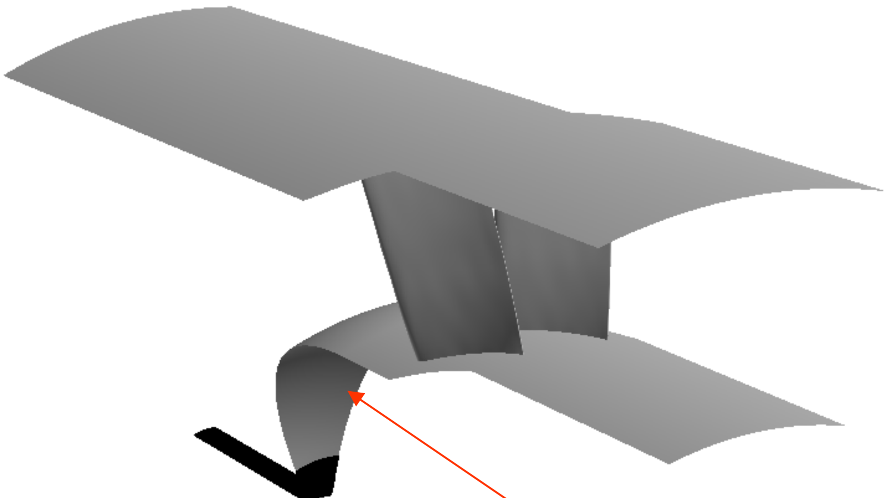
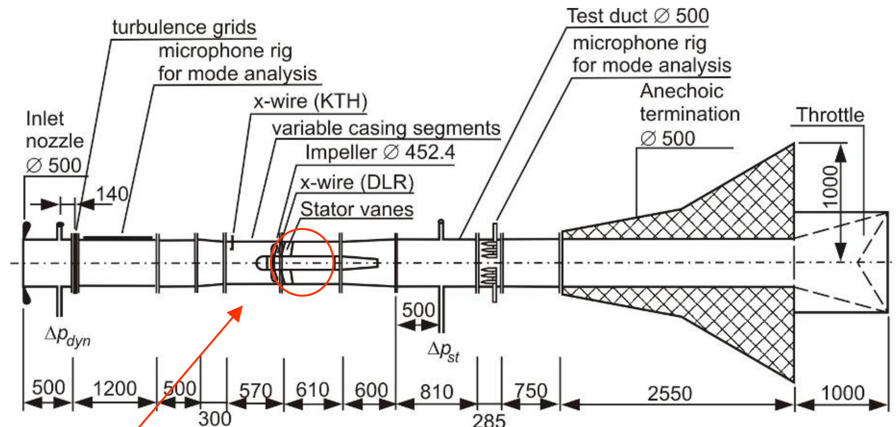
RANS Calculations for DLR Low Speed Fan (RR)

RANS study of effect of including upstream centrebody as part of the CFD mesh





Centrebody added upstream of rotor blade

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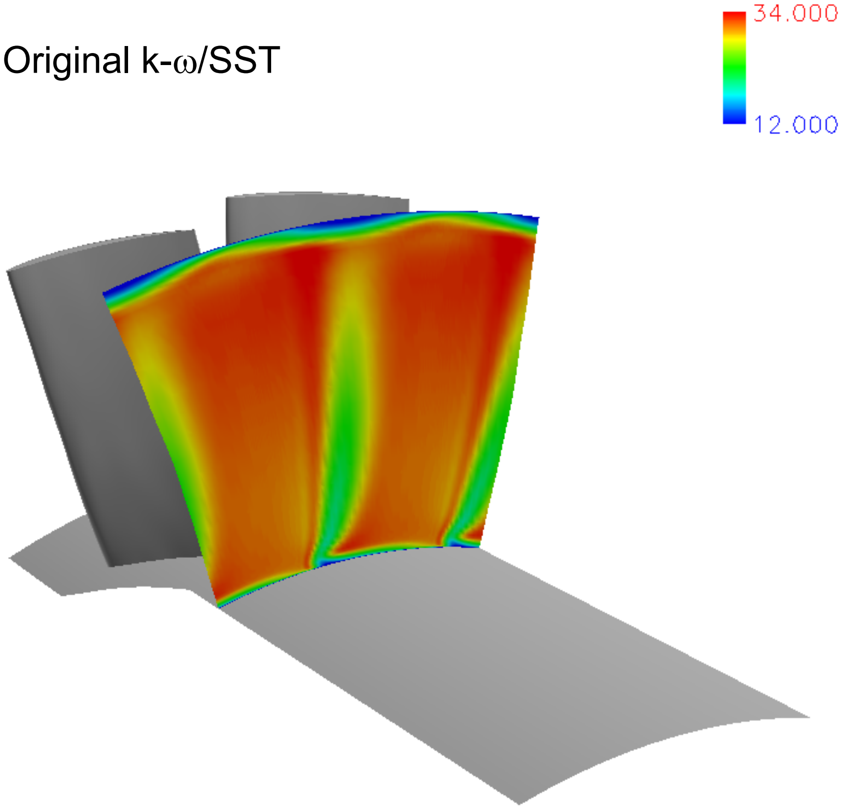
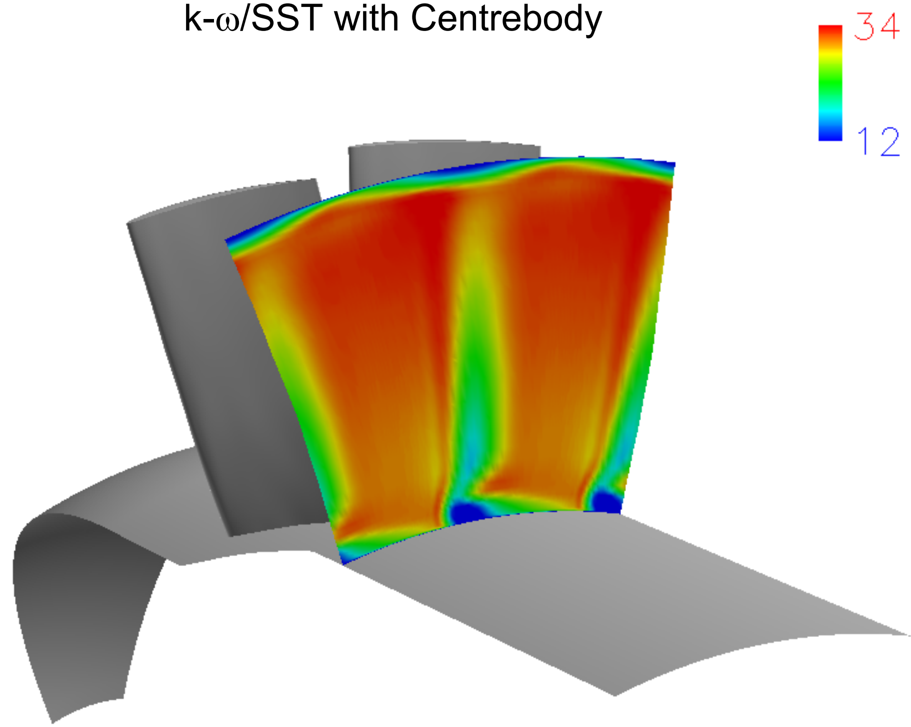
Axial Velocity at plane X2, Downstream of Rotor

Original k-ω/SST



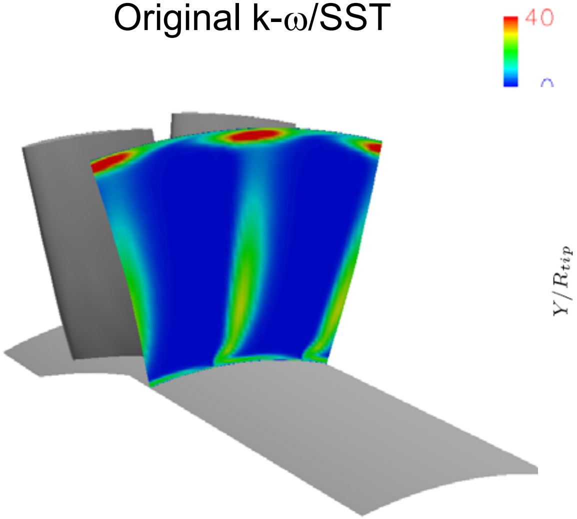
k-ω/SST with Centrebody



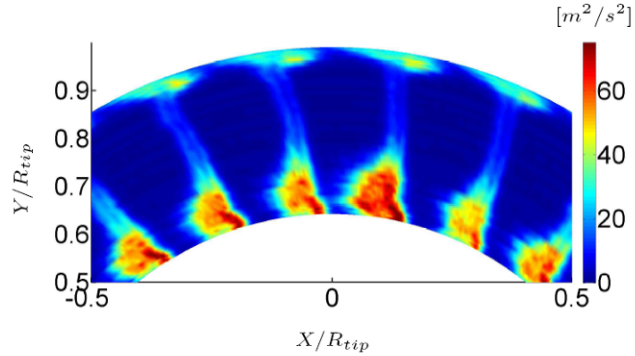
RANS Calculations for DLR Low Speed Fan (RR)

Turbulence Energy at plane X2, Downstream of Rotor

Original k-ω/SST

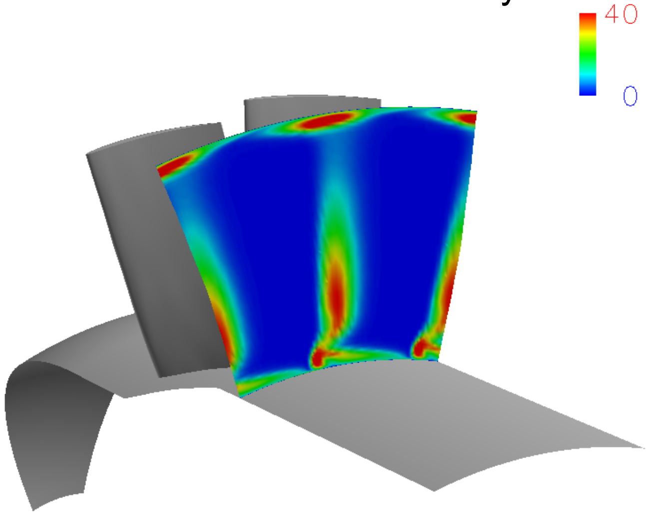


Experiment



(a) Measured turbulence energy at x_2

k-ω/SST with Centrebody



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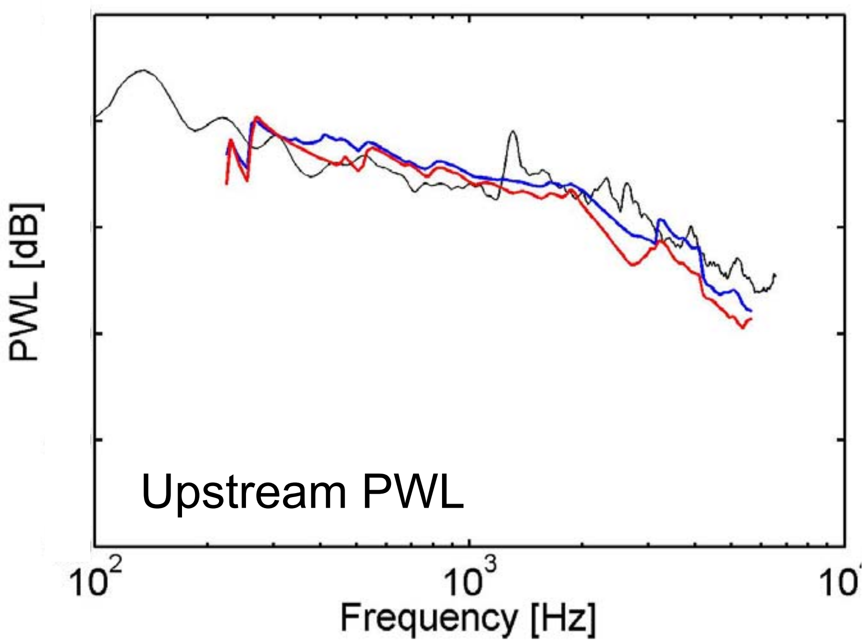
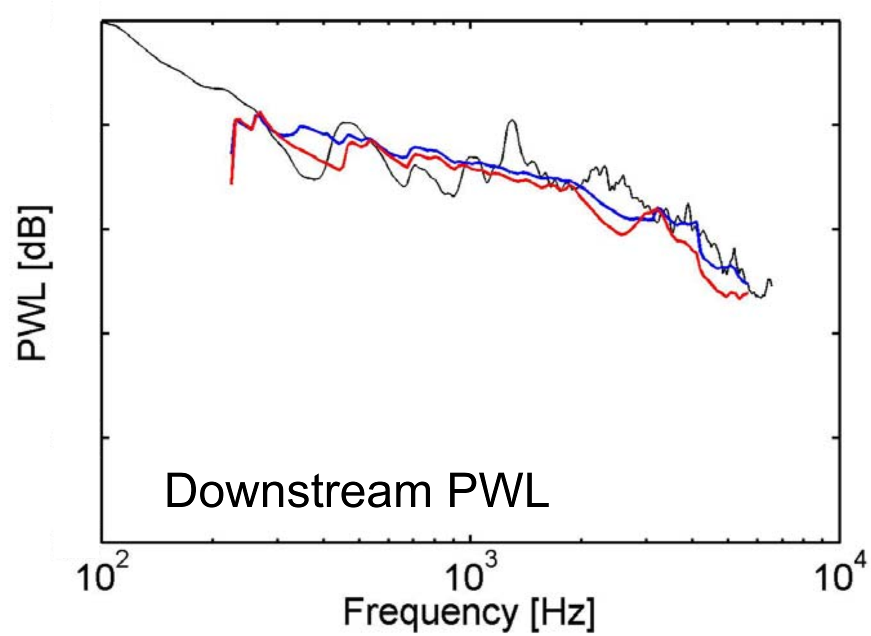
(Semi)analytical modelling (ISVR)





The broadband noise model was fed with Tu-levels from the experiments and with the outcome of a RANS calculation.

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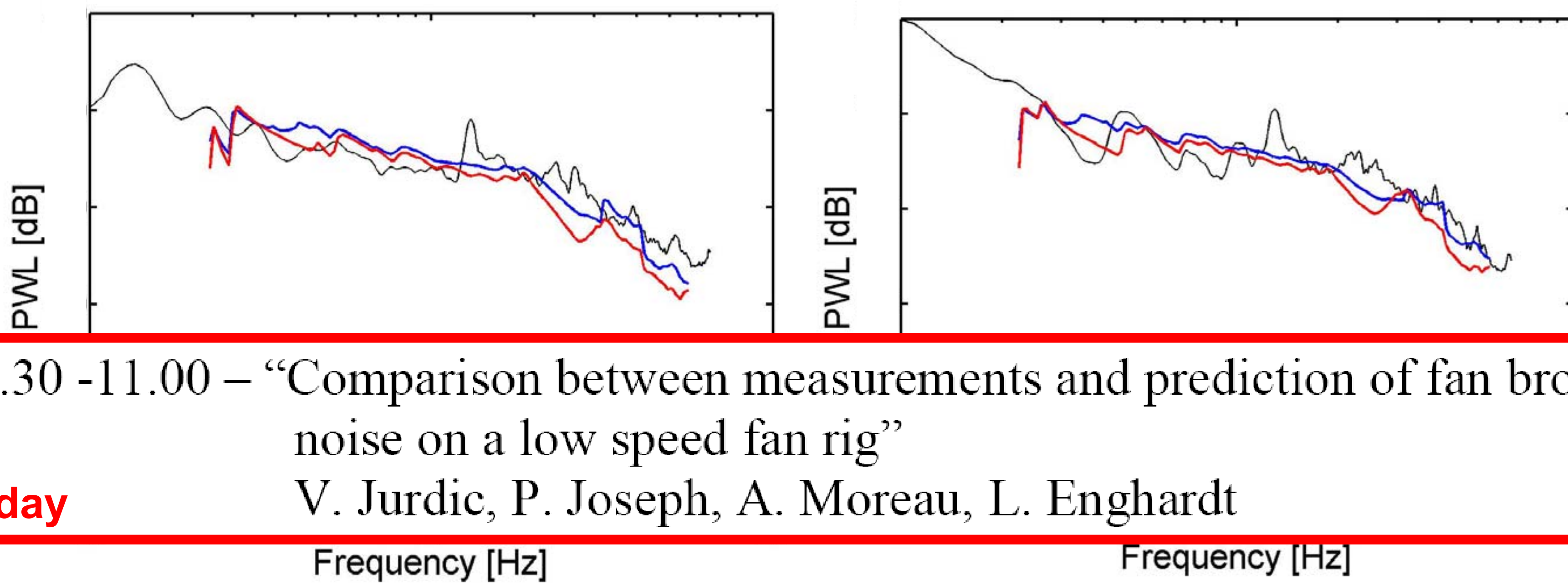
(Semi)analytical modelling (ISVR)



10.30 -11.00 – “Comparison between measurements and prediction of fan broadband noise on a low speed fan rig”

today V. Jurdic, P. Joseph, A. Moreau, L. Enghardt

The broadband noise model was fed with Tu-levels from the experiments and with the outcome of a RANS calculation.

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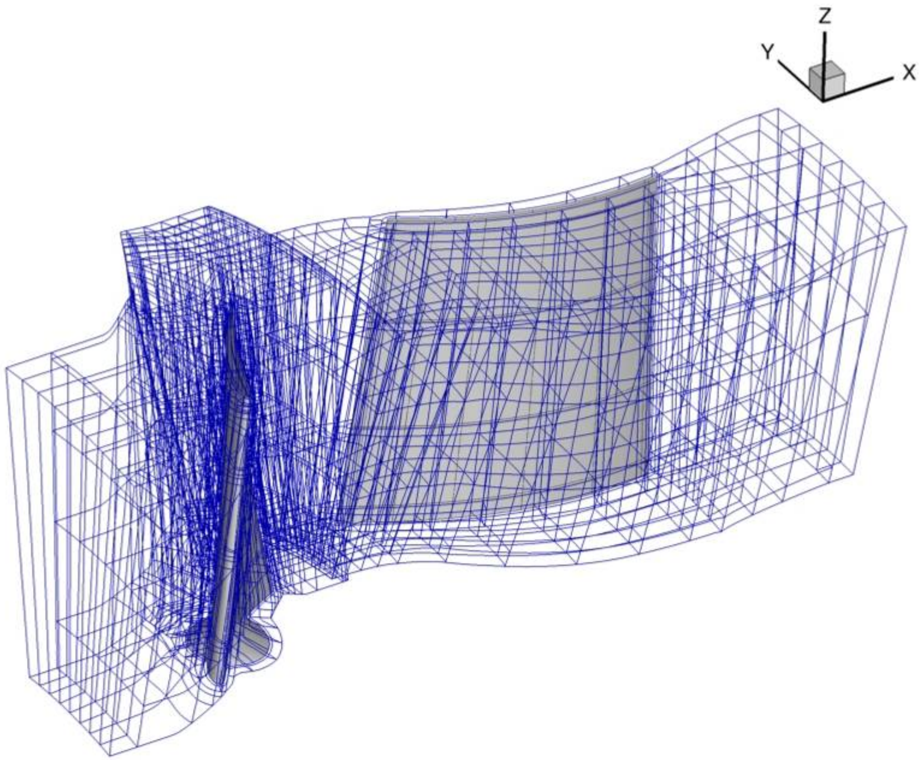
LES computations (DLR)



Multi-block structure of the LES mesh

Domain:

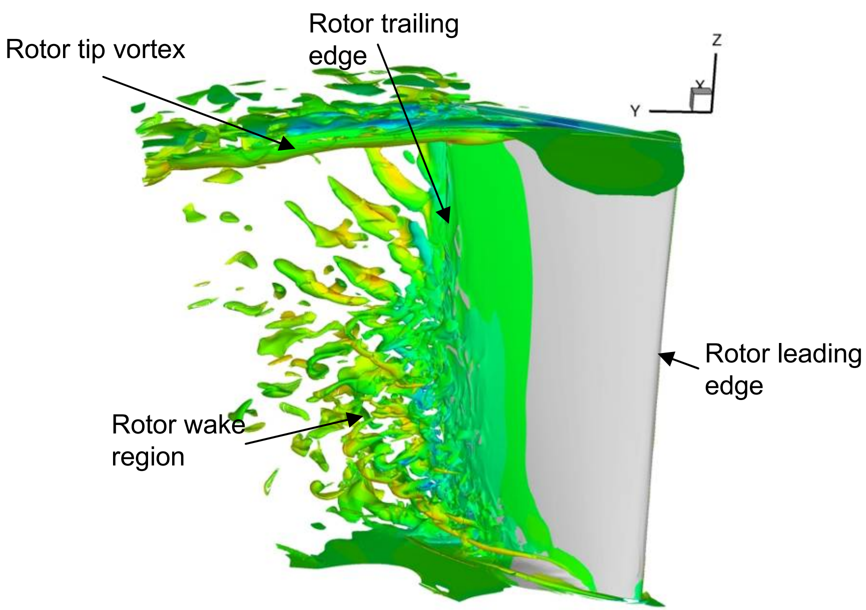
- Resolves 1 rotor passage and 1 stator passage
- Upper and lower boundaries directly connected (flow assumed periodic)
- Extends 1 rotor chordlength upstream/downstream of stage

Mesh:

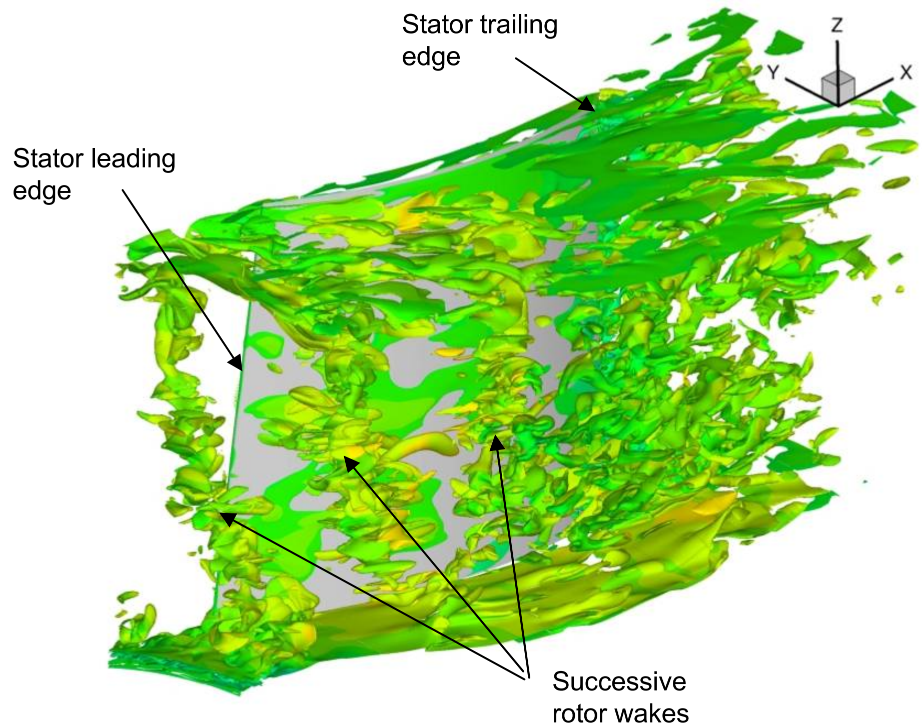
- 100×10^6 cells over 1100 blocks
- Span resolved with 600 cells
- Tip resolved with 45 cells
- Low-Reynolds

LES computations (DLR)

Computed turbulent flow structures



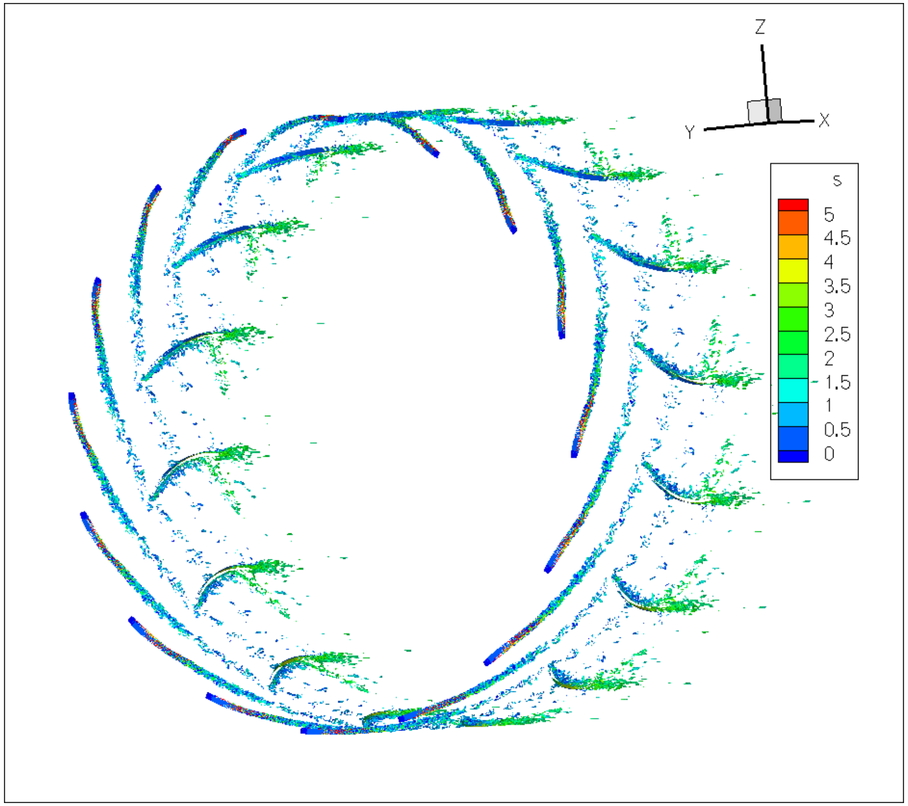
Iso-surfaces of the axial component of vorticity in rotor system.



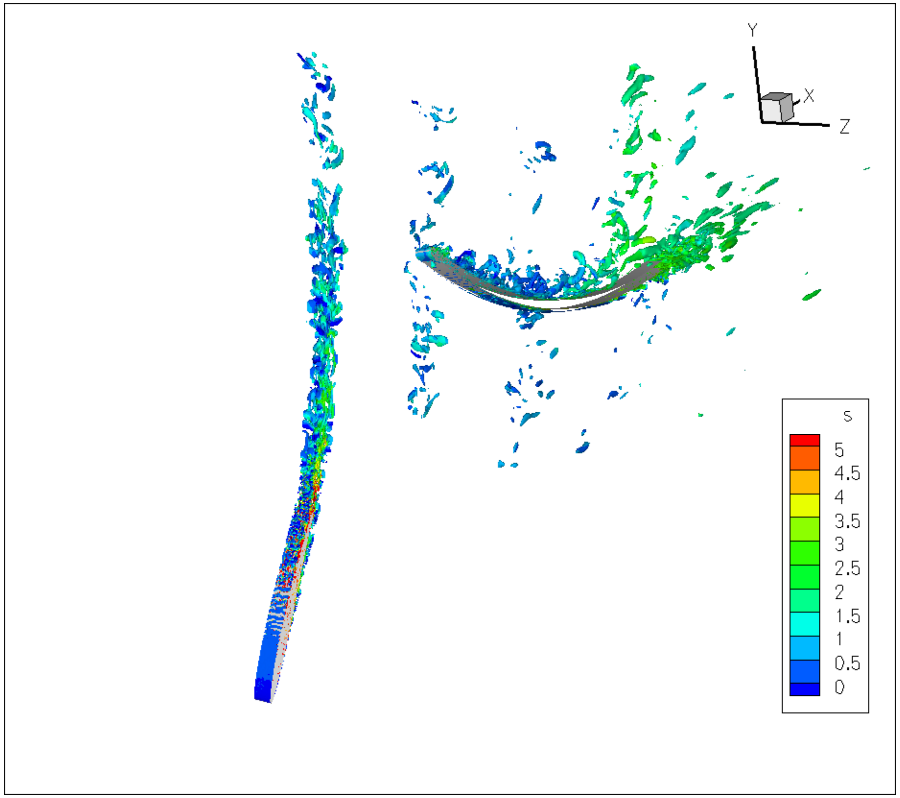
Iso-surfaces of the axial component of vorticity in stator system.

LES computations (ONERA)

Rotor-stator interaction



Close view of
blade-vane interaction



Iso-surface of *Q* colored by entropy

LES computations (ONERA)

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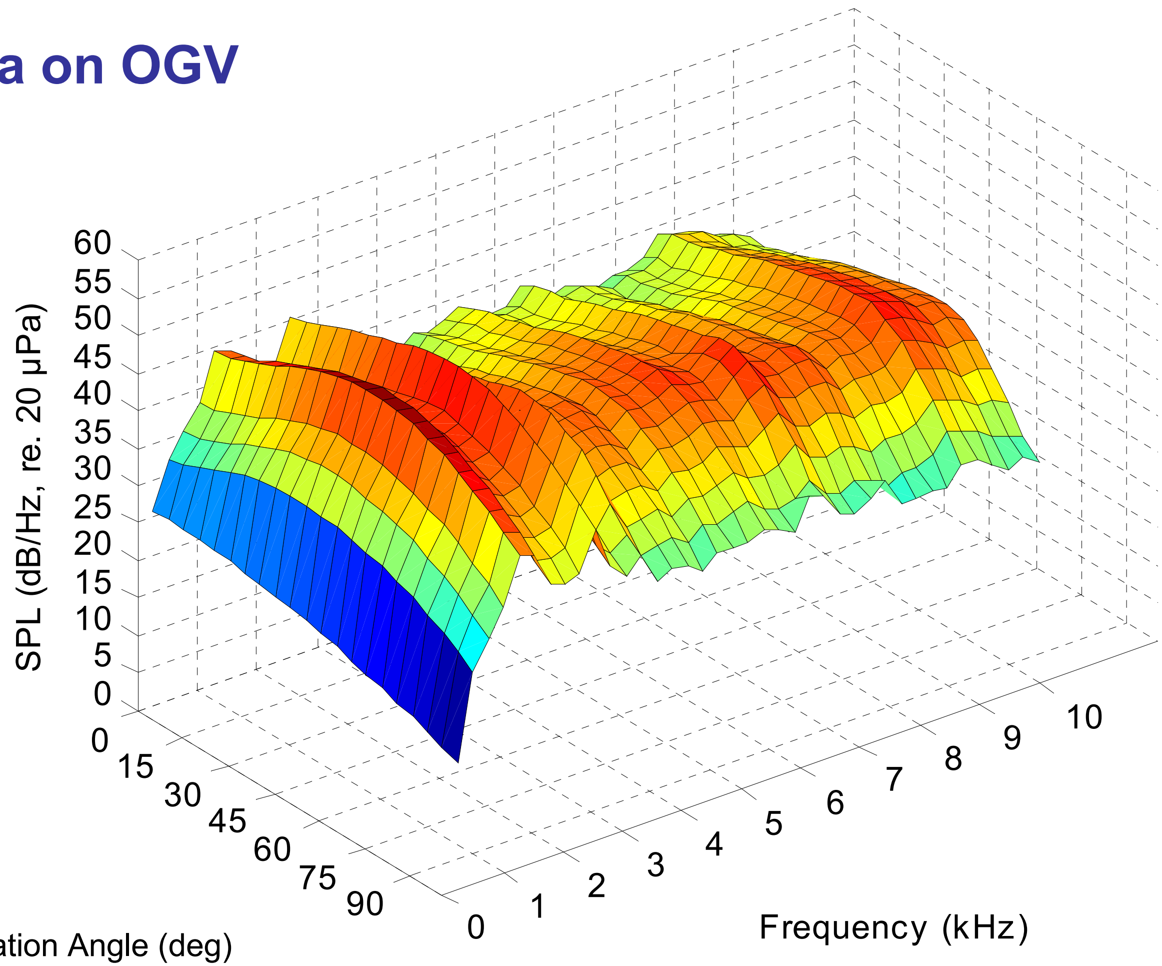
Far-field acoustic radiation

Input: LES data on OGV



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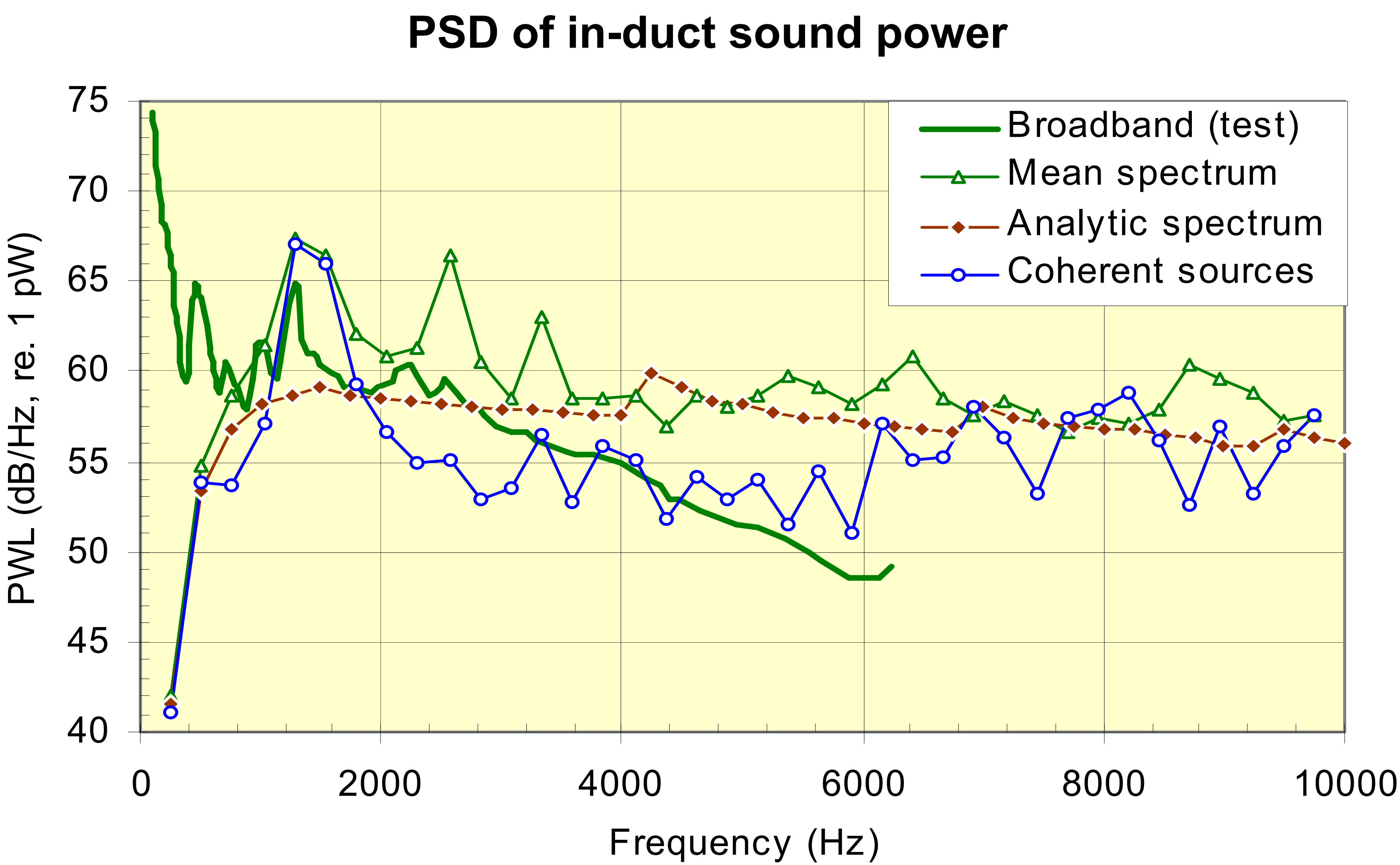
LES computations (ONERA)



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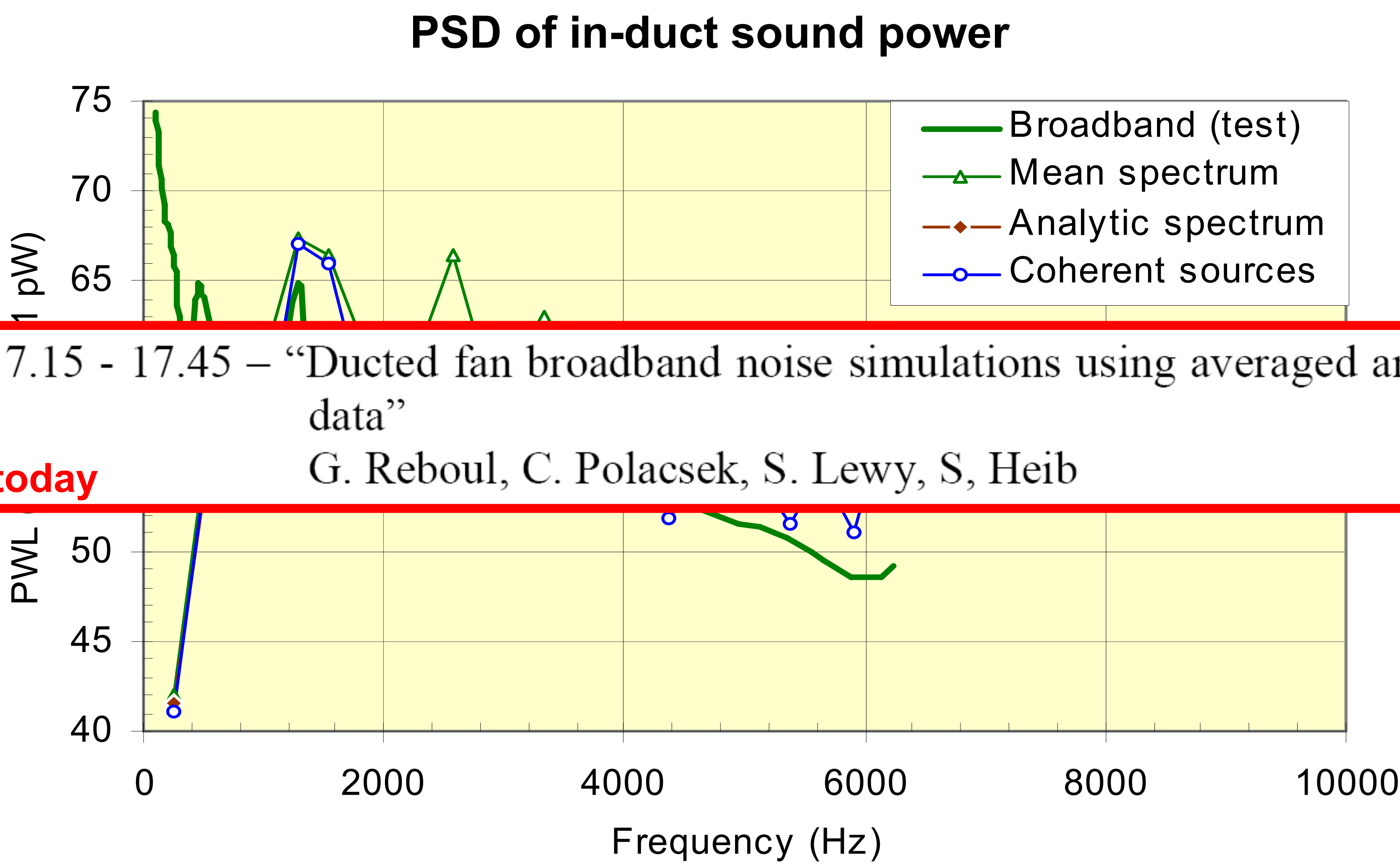
LES computations (ONERA)



17.15 - 17.45 – “Ducted fan broadband noise simulations using averaged and unsteady data”

G. Reboul, C. Polacsek, S. Lewy, S, Heib

today

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WP4: Industrial Fan-OGV noise: Methods Validation and Demonstration

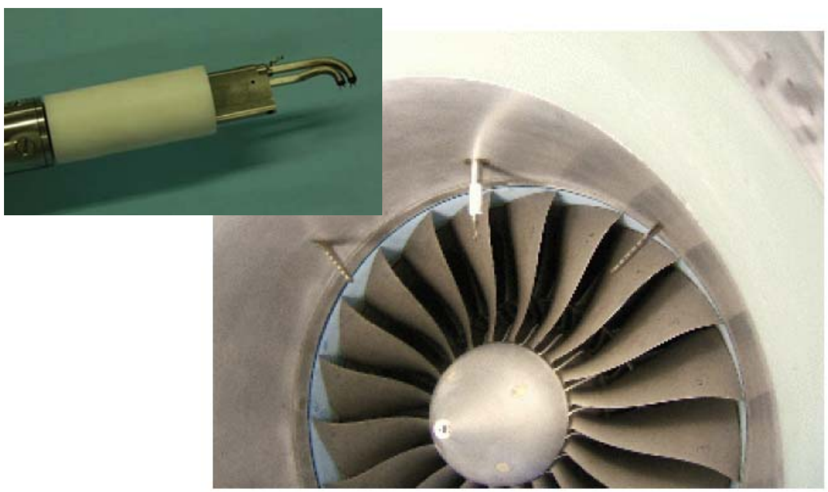
Objective

- Validation and demonstration of the computational methods developed and assessed in WP2 and WP3

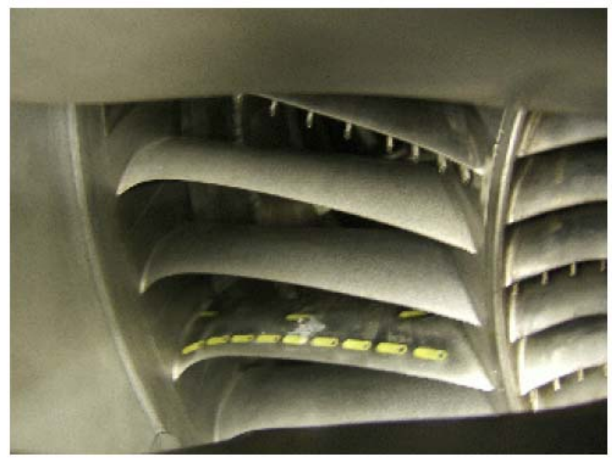
Setup of industrial fan experiment (ACAT, RR, VKI)

(a) Fan rig installed in anechoic chamber

(b) Fan-OGV gap hot wire probe



(c) Inlet flow hot-wire probe



(d) Bypass OGV with Kulites

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Pressure measurements on OGV (DLR)

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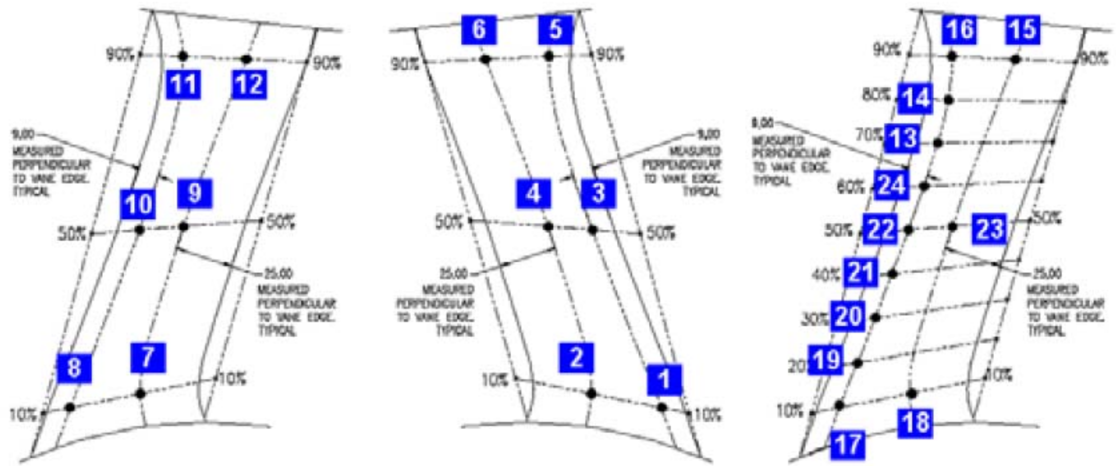
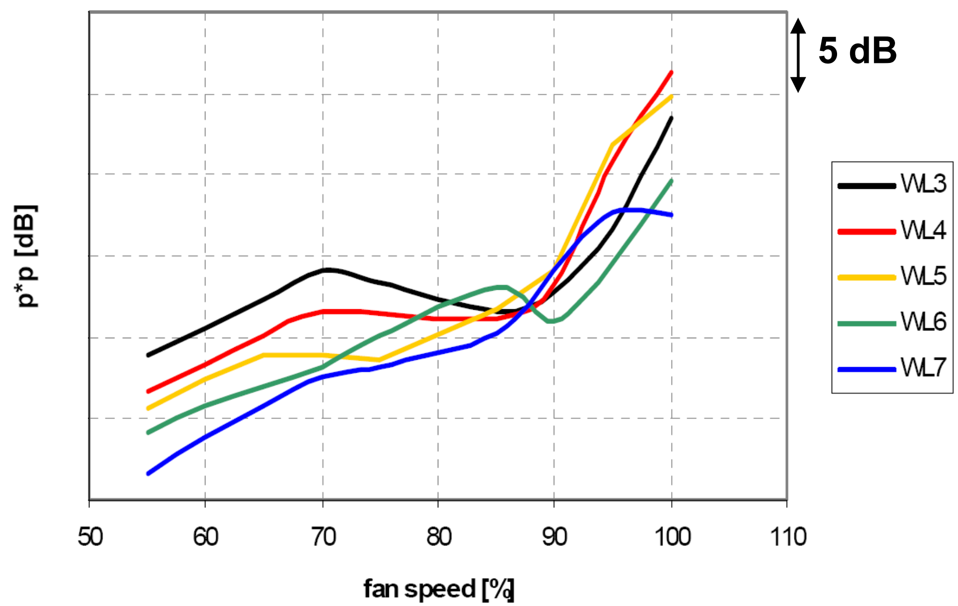
Pressure sensor arragement on stator vane surfaces

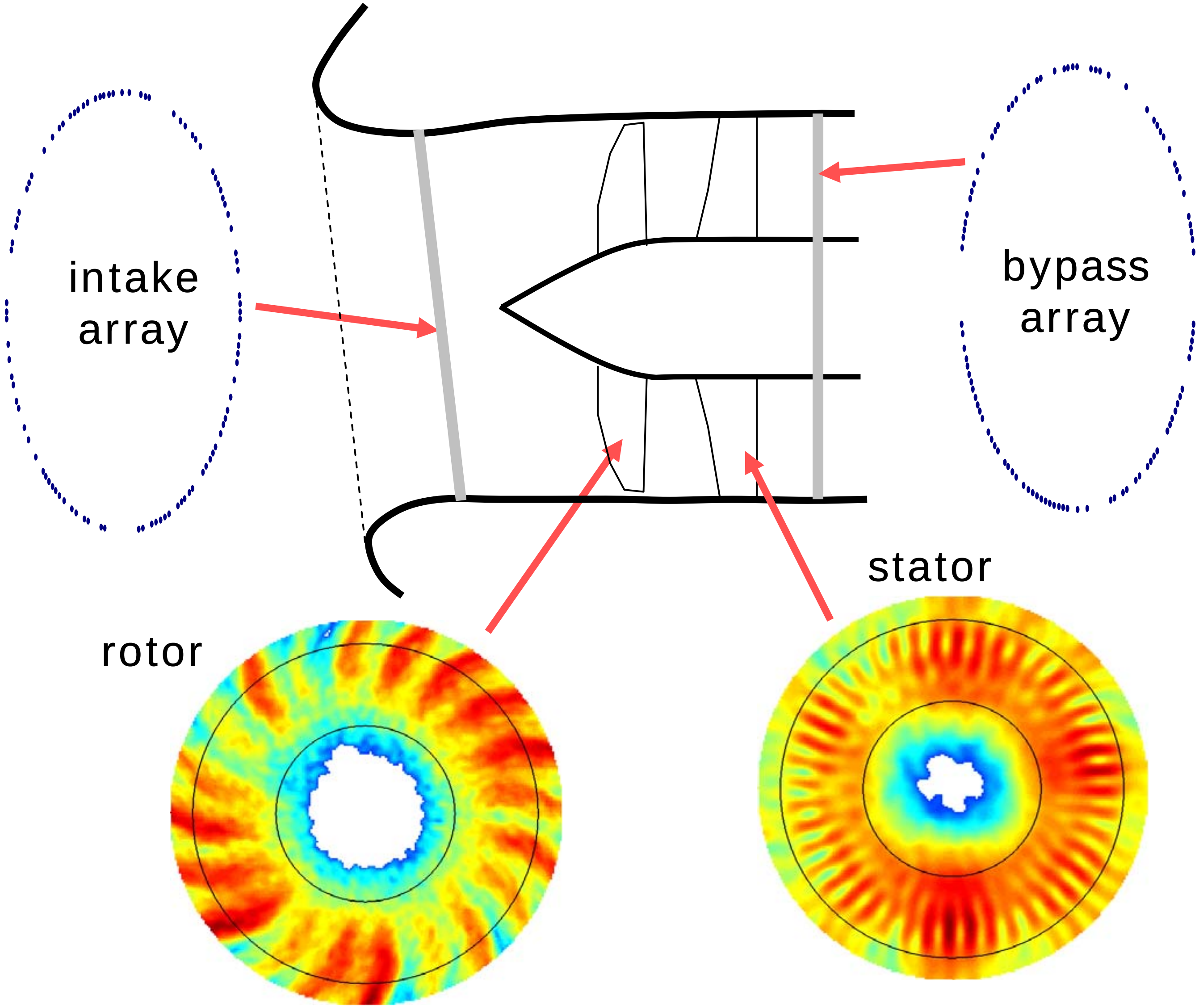


Variation of total broadband surface autopower levels for five working lines

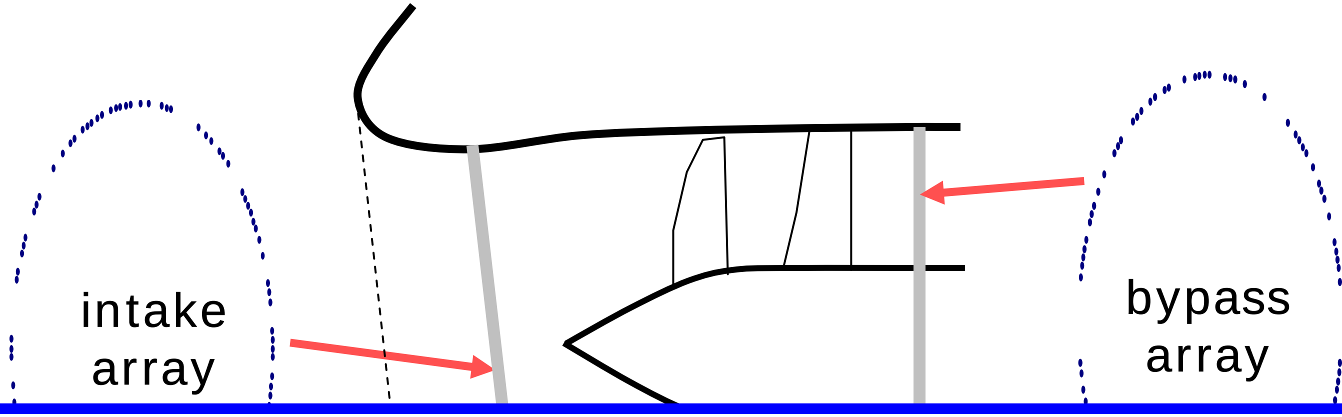


EU Framework 6 Research

Induct Beamforming (NLR)

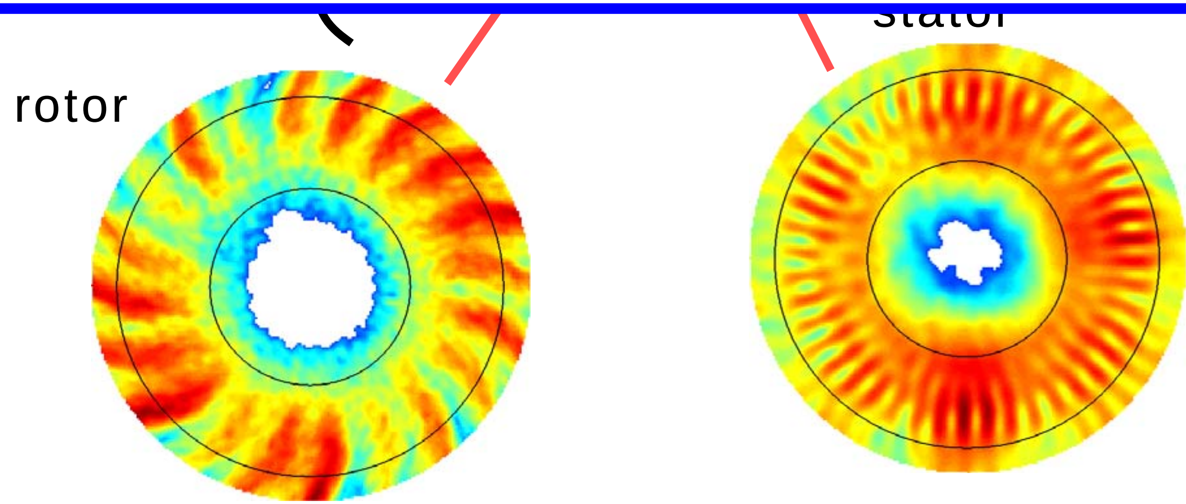


Induct Beamforming (NLR)



9.15 - 10.00 - INVITED LECTURE: "Using Phased Array Beamforming to Identify Broadband Noise Sources in a Turbofan Engine"
P. Sijtsma, NLR, The Netherlands

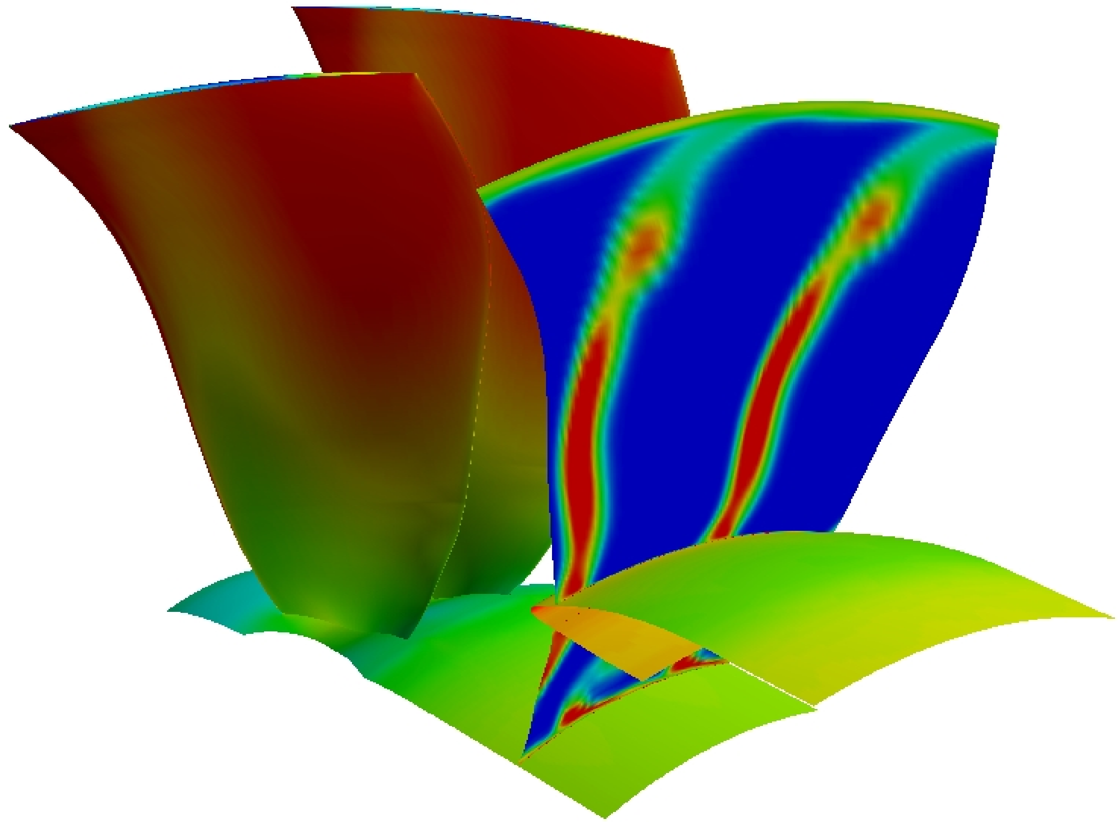
tomorrow



EU Framework 6 Research

Industrial Test Rig RANS result (RR)

Turbulence Energy, k (m^2/s^2)



Fan Blade

High Fan Speed (transonic flow)

k-ω/SST RANS

Wake data extracted on OGV "leading edge plane" → Noise Models

Industrial Test Rig RANS result (RR)

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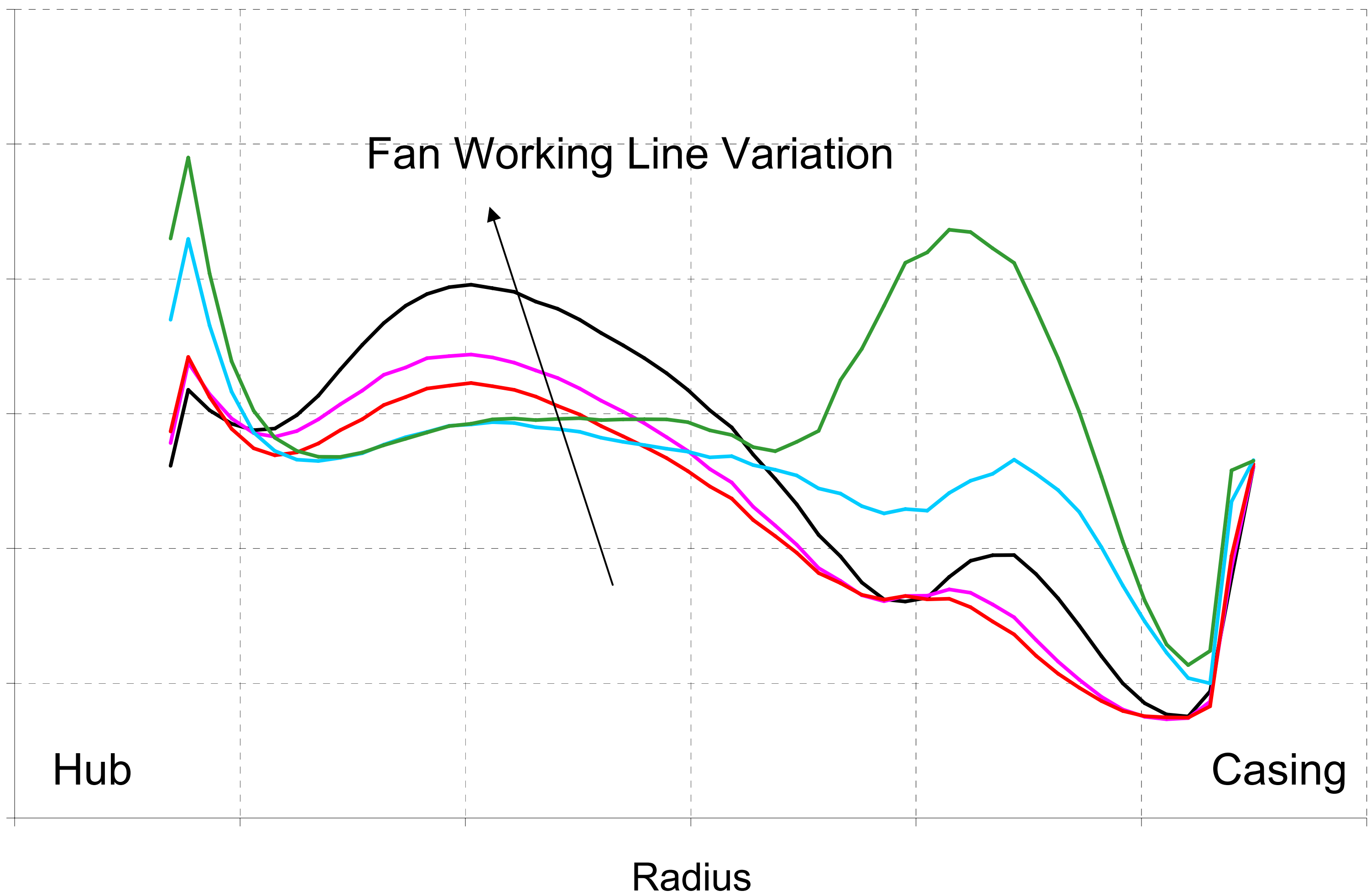
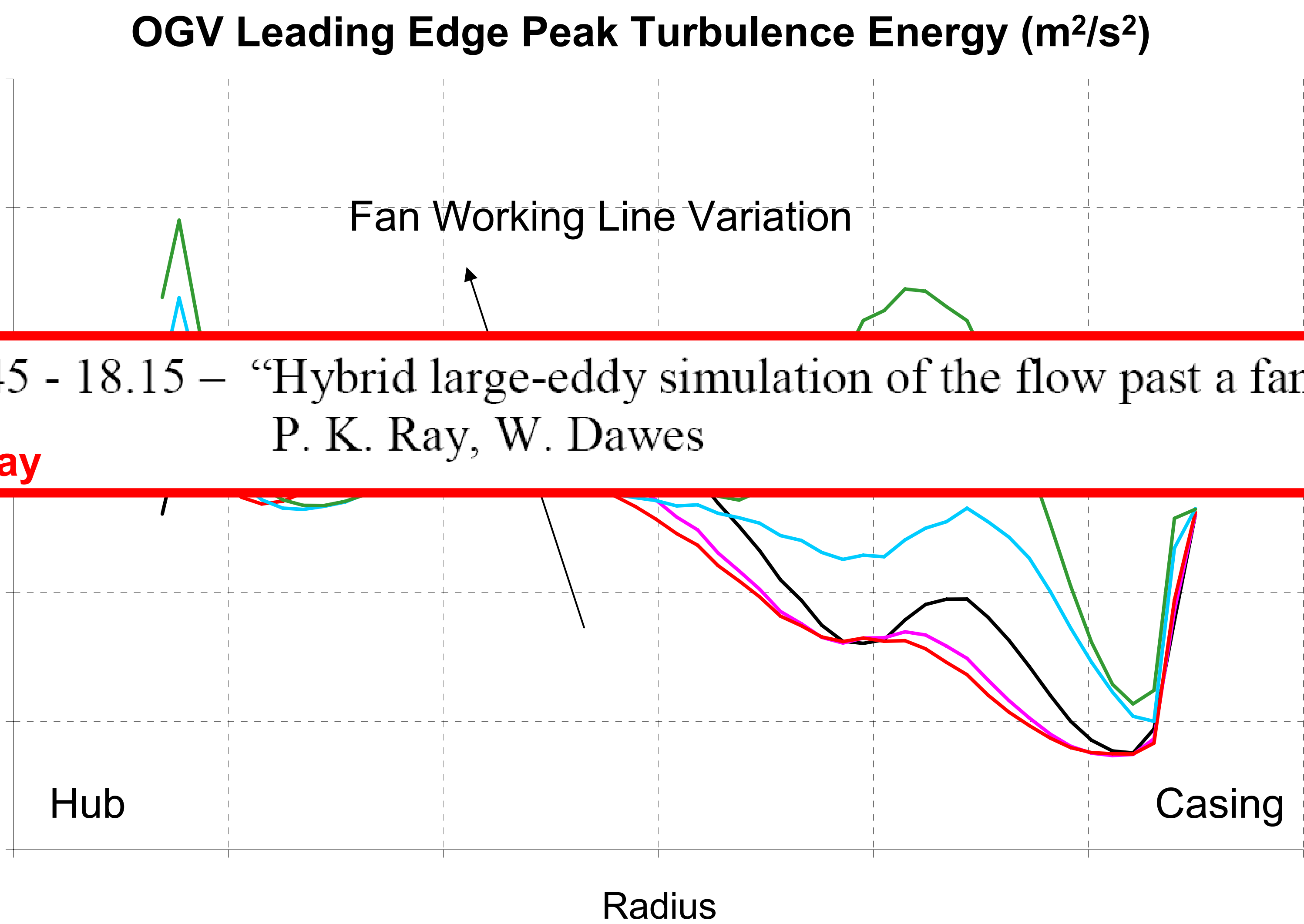
OGV Leading Edge Peak Turbulence Energy (m²/s²)



Industrial Test Rig RANS result (RR)



17.45 - 18.15 – "Hybrid large-eddy simulation of the flow past a fan-blade section"
P. K. Ray, W. Dawes

today

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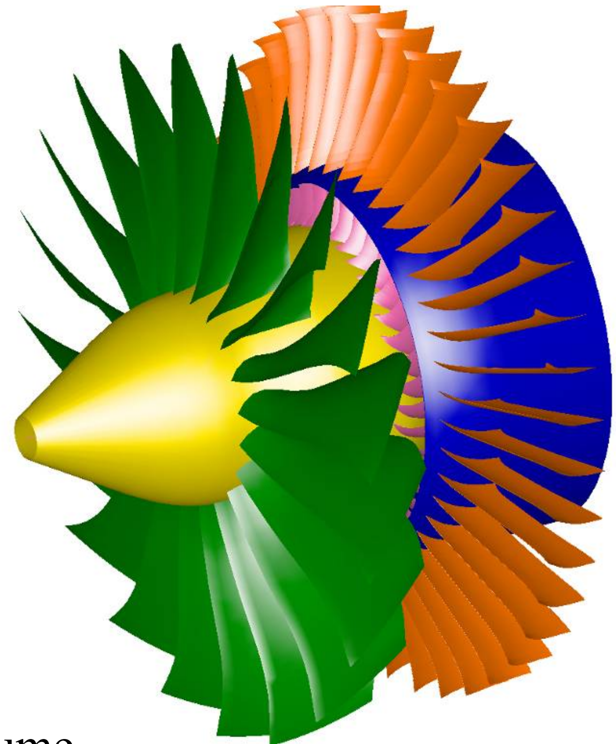
EU Framework 6 Research

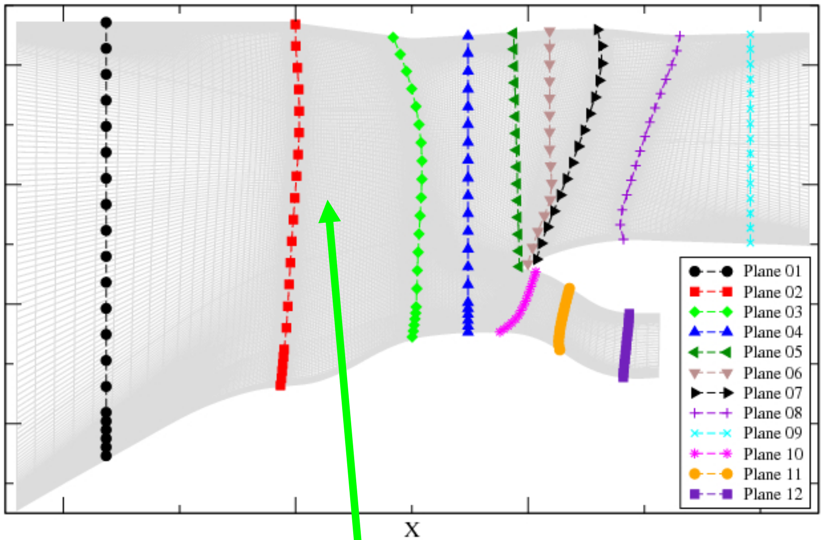
CFD of FAN-OGV-ESS: characteristics (FLU)

- Industrial test rig, including rotating fan and two stator vanes (bypass and core ducts)
- Number of blades: FAN=20, OGV=44 modelled by a 1:2 ratio
- 3D N.S. compressible simulation realized at Fluorem with Turb'Flow® :



- High fan speed (transonic flow)
- **≈ 6500000** grid nodes, Multiblock structured finite volume
- Upwind spatial scheme 3rd order with limiters (because flow field with shocks)
- Explicit 5 steps Runge Kutta time marching with **1500000** Δt per 360° rotation
- Rotor-stator interactions modeled by a sliding mesh technique using DFT
- **Hybrid RANS-Wilcox / LES-WALE** (Wall Adapting Large Eddy following Nicoud and Ducros, *Flow turbulence and combustion* 62:183-200, 1999)
- Computations realized on 24 CPU cores (AMD Opteron® @2400 Mhz)

CFD of FAN-OGV-ESS: Mean meridian flow (FLU)

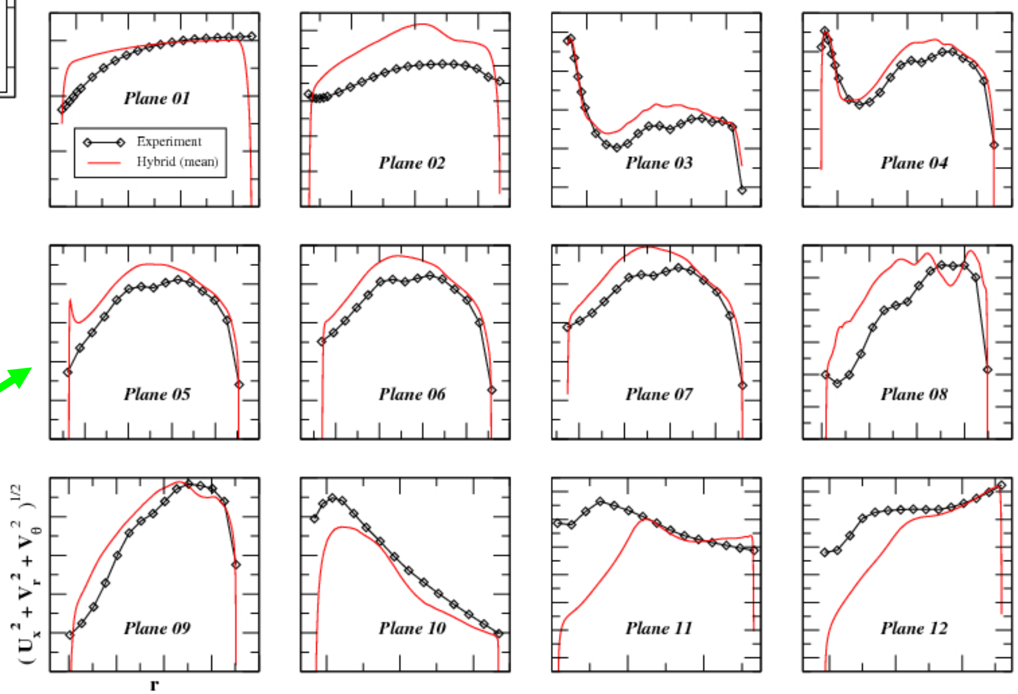


Sample hyb. RANS-LES results :

Azimuthal and temporal averages of aerodynamic fields

Locations of experimental measurement sections in the *x-r* meridian mesh

Meridian mean total velocities



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CFD of FAN-OGV-ESS: Acoustics (FLU)

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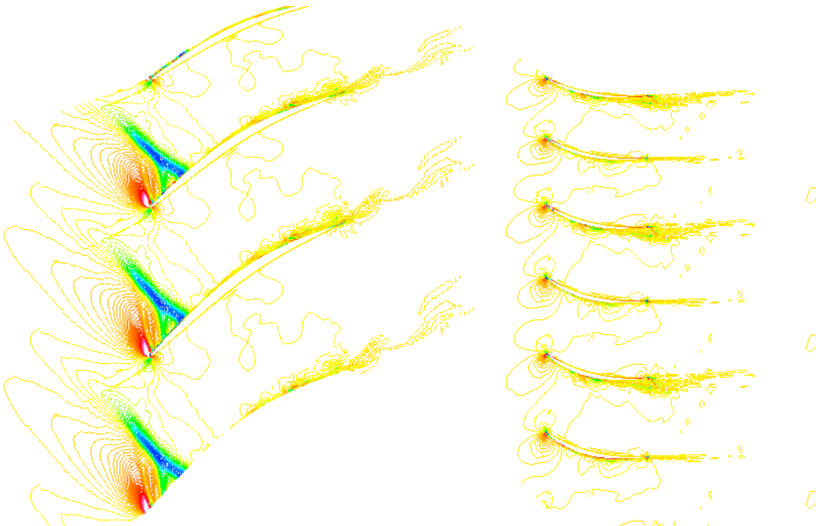
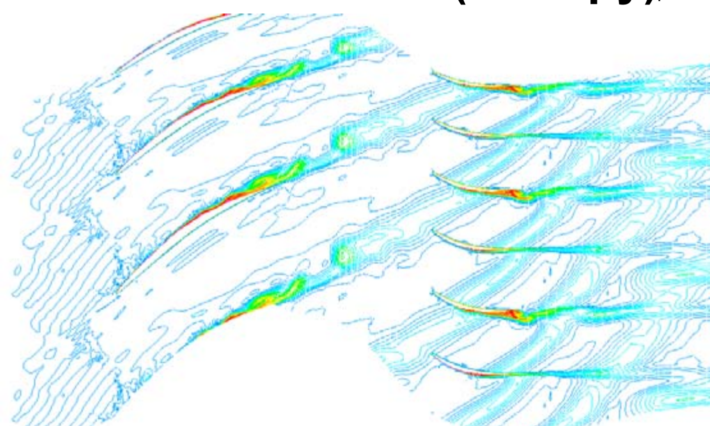
Instantaneous velocity divergence



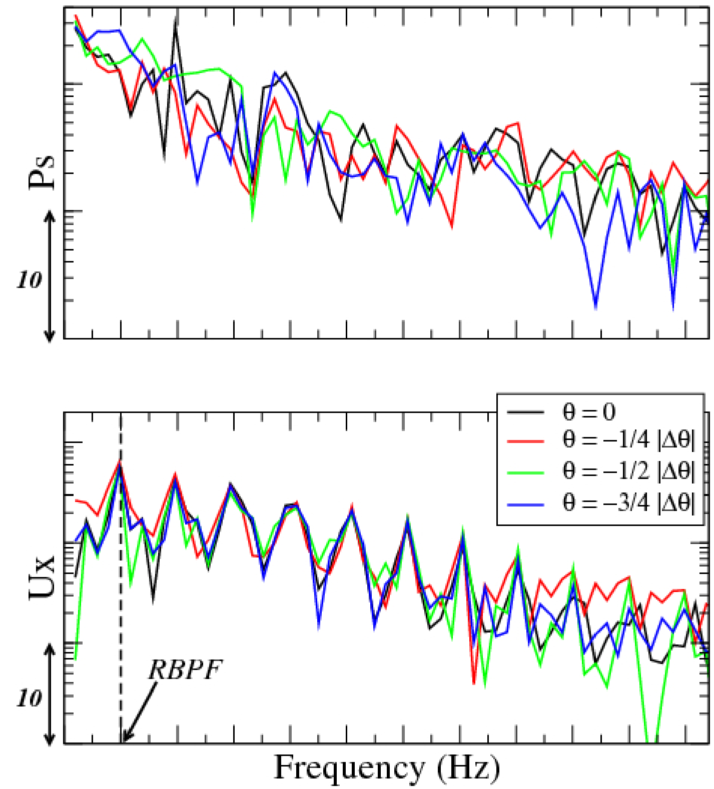
Wake visualizations (entropy)



Next steps :

- Characterization of near field acoustic sources
- Far field noise propagation

Pressure and Velocity spectra at the stator inlet



EU Framework 6 Research

Summary: Final results

- PROBAND enables improved physical understanding of the source mechanisms of self noise, interaction noise, and tip clearance noise. The fundamental experiments provide, in conjunction with advanced CFD, a deeper insight into the flow physics in the source regions.

- PROBAND has developed new tools allowing large scale advanced CFD, and validated them in a realistic experimental environment.

- PROBAND delivers an improved prediction capability for broadband noise that will be exploited by the European engine industry to develop low broadband noise fan concepts.