



# Turbofan and CROR noise simulations

*C. Polacsek*

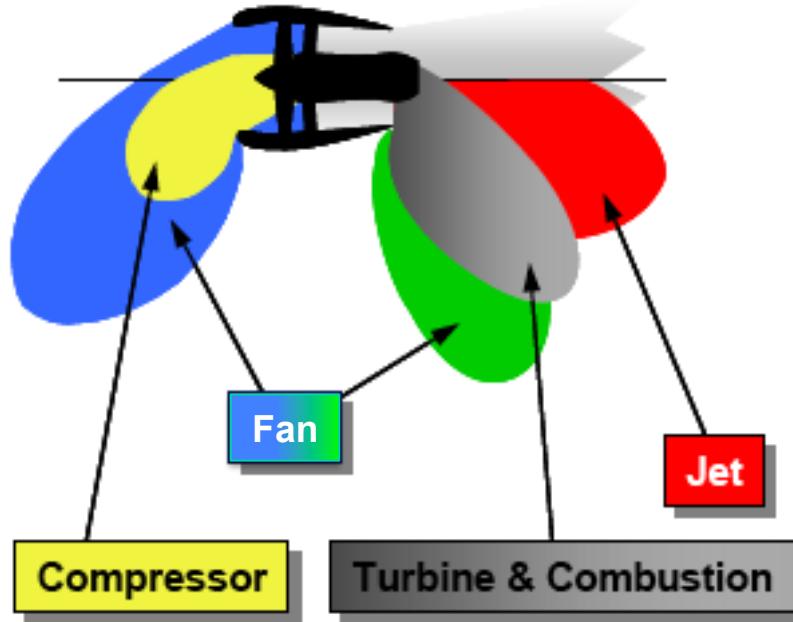


r e t o u r s u r i n n o v a t i o n

# Outline

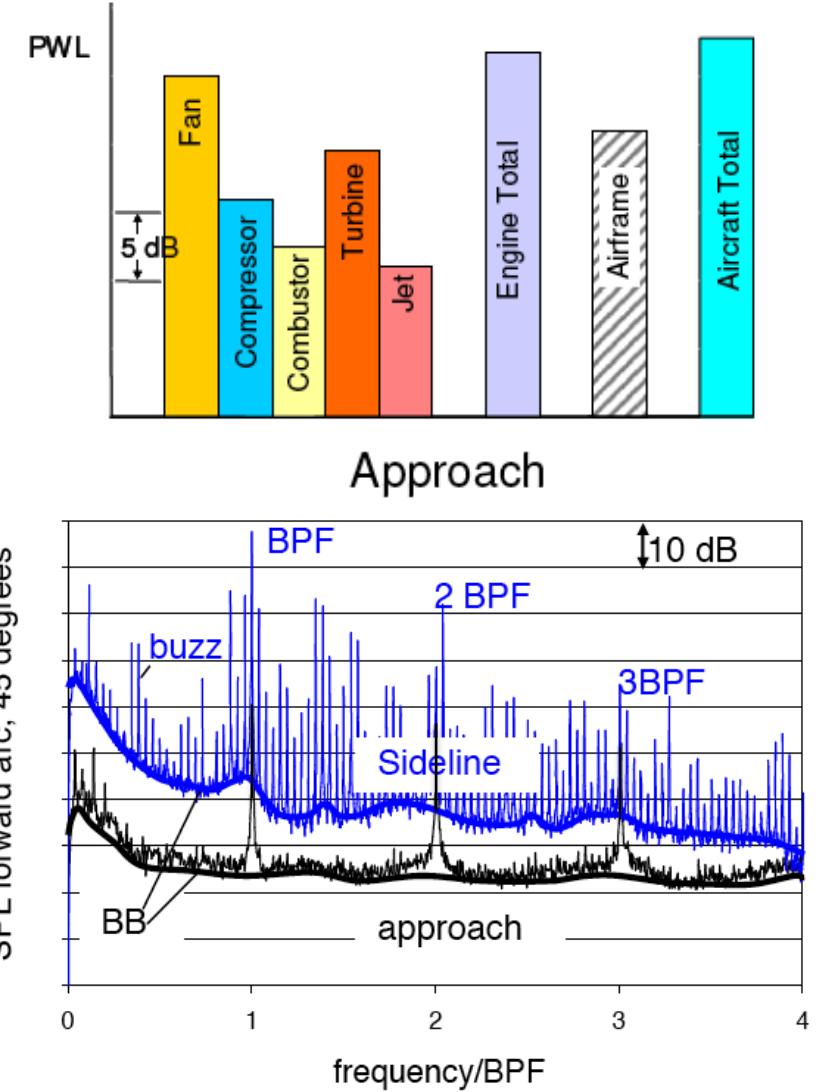
1. Aeroengine sources
2. Hybrid methodologies (CFD/CAA/modeling)
3. Tone noise (periodic wake interaction) simulations
  - Rotor-stator basic configuration (LNR2 fan model)
  - Contra-rotating turbofan (CRTF)
  - LEAP engine with heterogeneous OGV & pylones
4. Broadband noise (turbulent wake interaction) simulations
  - LES (or DES) based computations
  - Stochastic model + CAA
5. Challenge & perspectives

# Aeroengine source component distribution

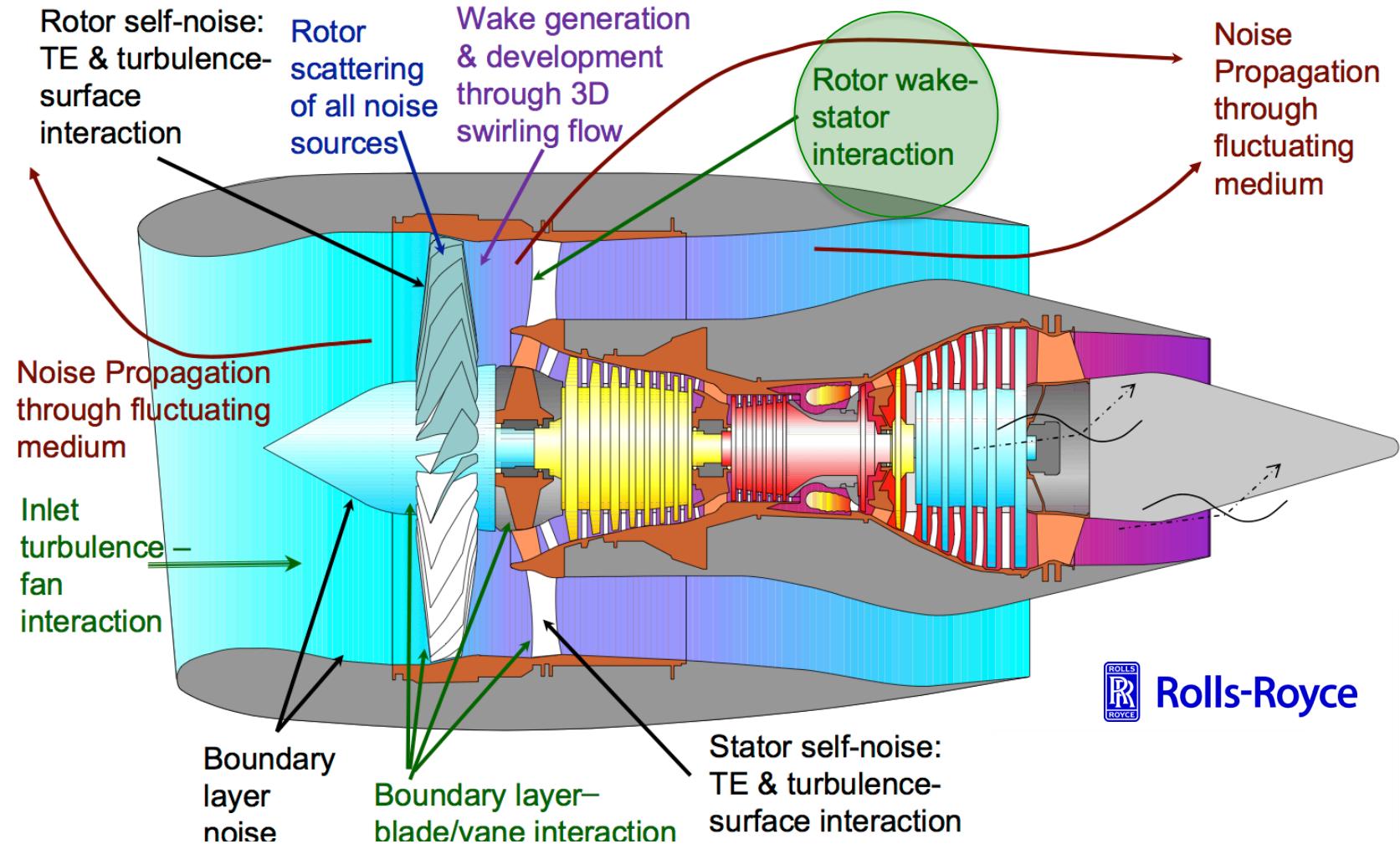


## Fan component

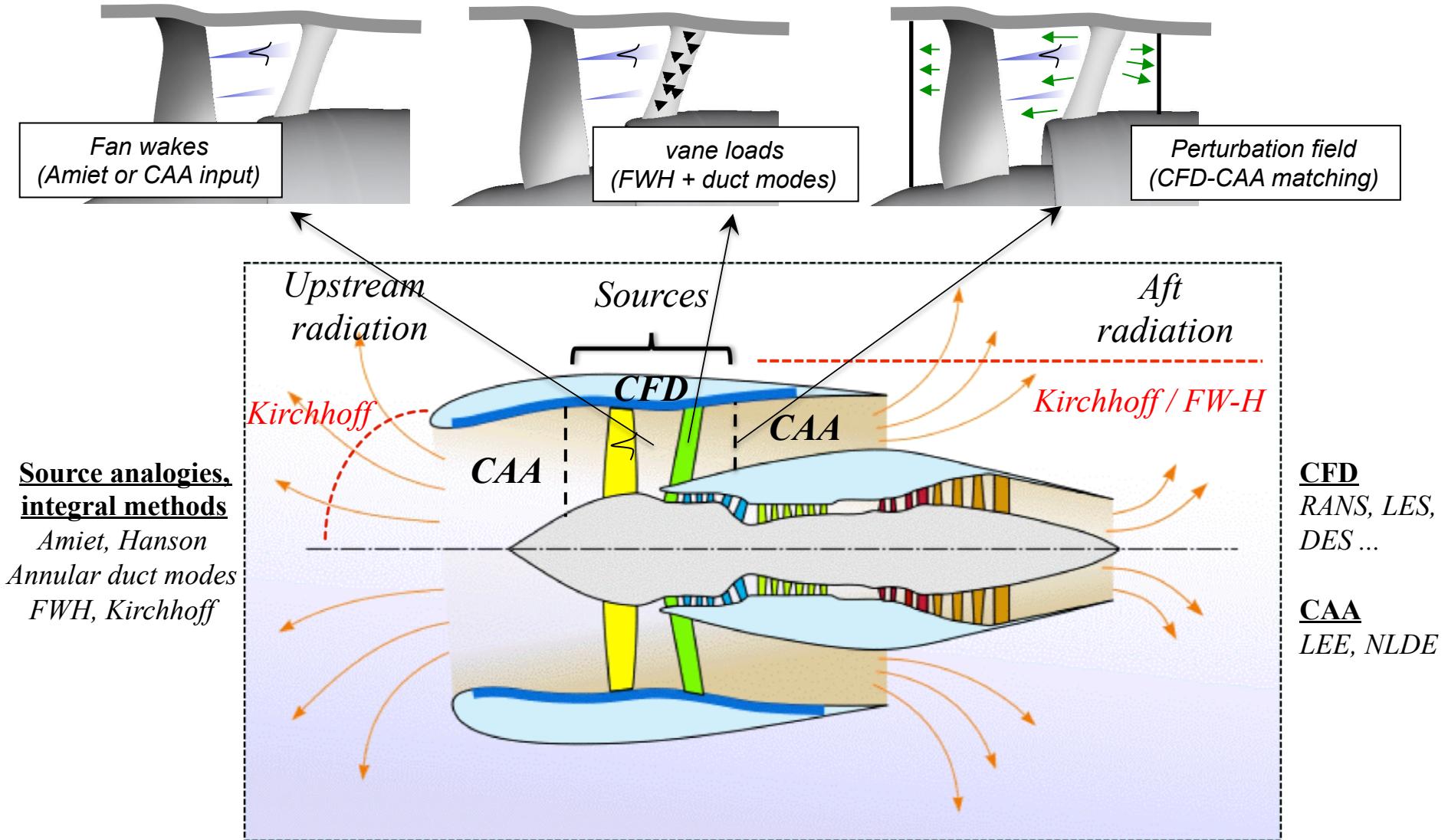
- Dominant source at approach conditions
- Interaction tones (rotor wake-OGV)
- Buzz saw noise in cruise conditions
- Broadband part contributing to OASPL



# Turbofan (broadband) sources



# Usual hybrid methodologies (fan-OGV interaction)



# Tone noise simulations

# URANS-based simulations for interaction noise (1)

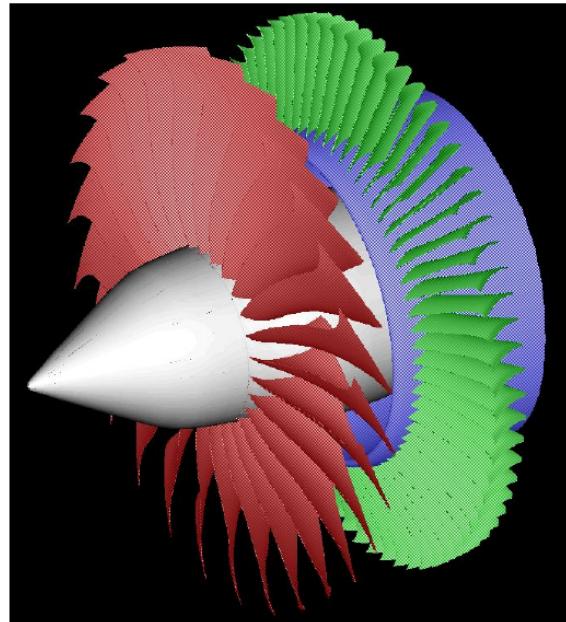
Turbofan (LNR2 model) configuration & CFD grid

LNR2 subsonic fan case	
Rotor blade number (B)	26
Stator vane number (V)	58
Rotation speed (rot/min)	6 111
Blade Passing Frequency (Hz)	2 648
Outer radius (mm)	436
Axial mean Mach number	0.27

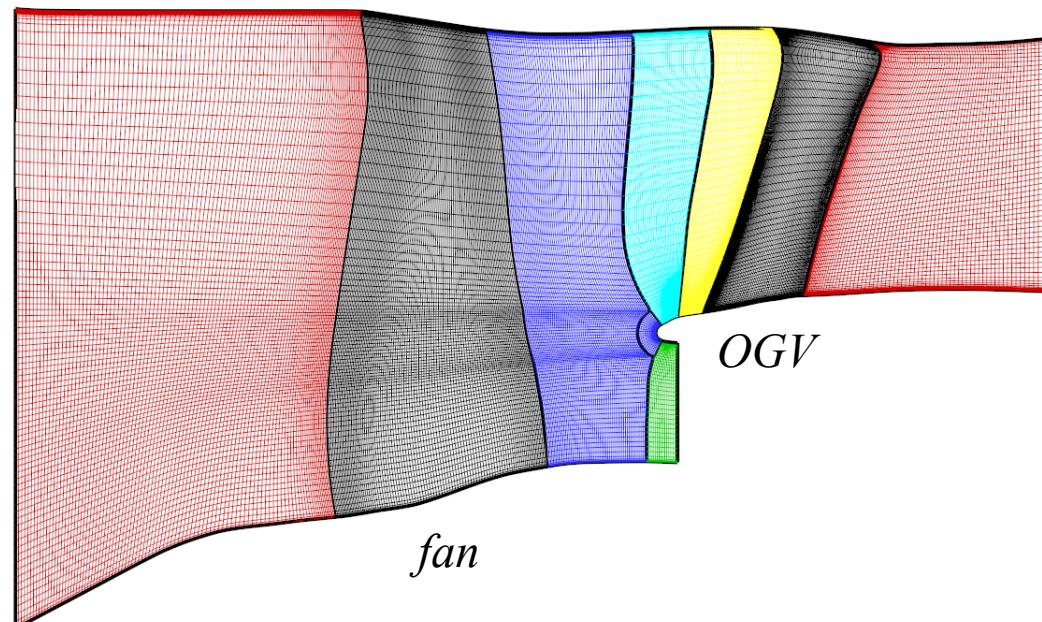
Interaction modes:  $m = nB - kV$   
(Tyler & Sofrin)

n harmonics	m	k blade load harmonics				
		-1	0	1	2	3
BPF 1	84	26	-32	-90	-148	
BPF 2	110	52	-6	-64	-122	
BPF 3	136	78	20	-38	-96	
BPF 4	162	104	46	-12	-70	

3D geometry of LNR2 model

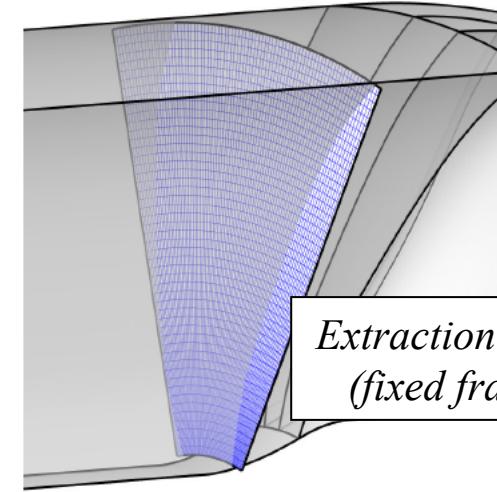
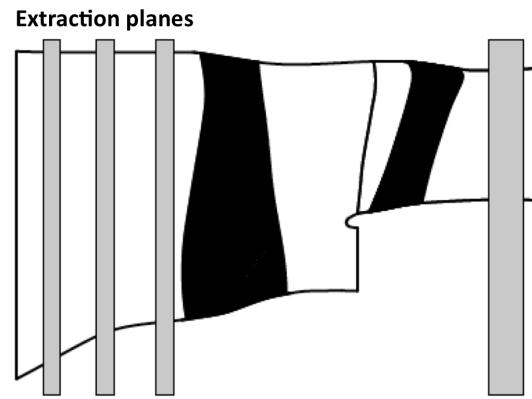
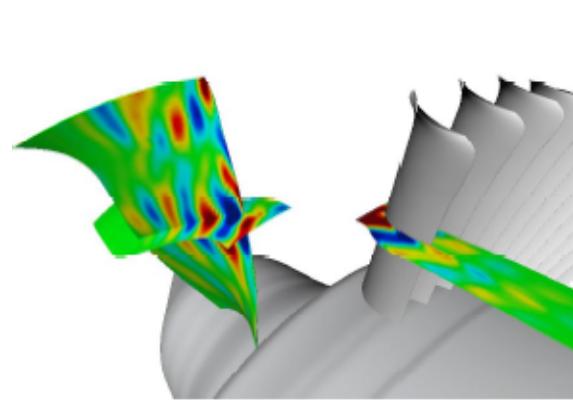


Section view of 3D grid



# URANS-based simulations for interaction noise (2)

CFD features (*elsA* code) & post-processing tool (*Zeppelin*)



## Standard URANS features using *elsA*

- Finite volume, structured multi-block
- 2<sup>nd</sup> order Jameson scheme
- $(k,L)$  turbulence model
- Chorochronic calculations
- NRBC: 1D-Thompson characteristics  
+ damping zone (stretching)
- Min 40 pts / wavelength

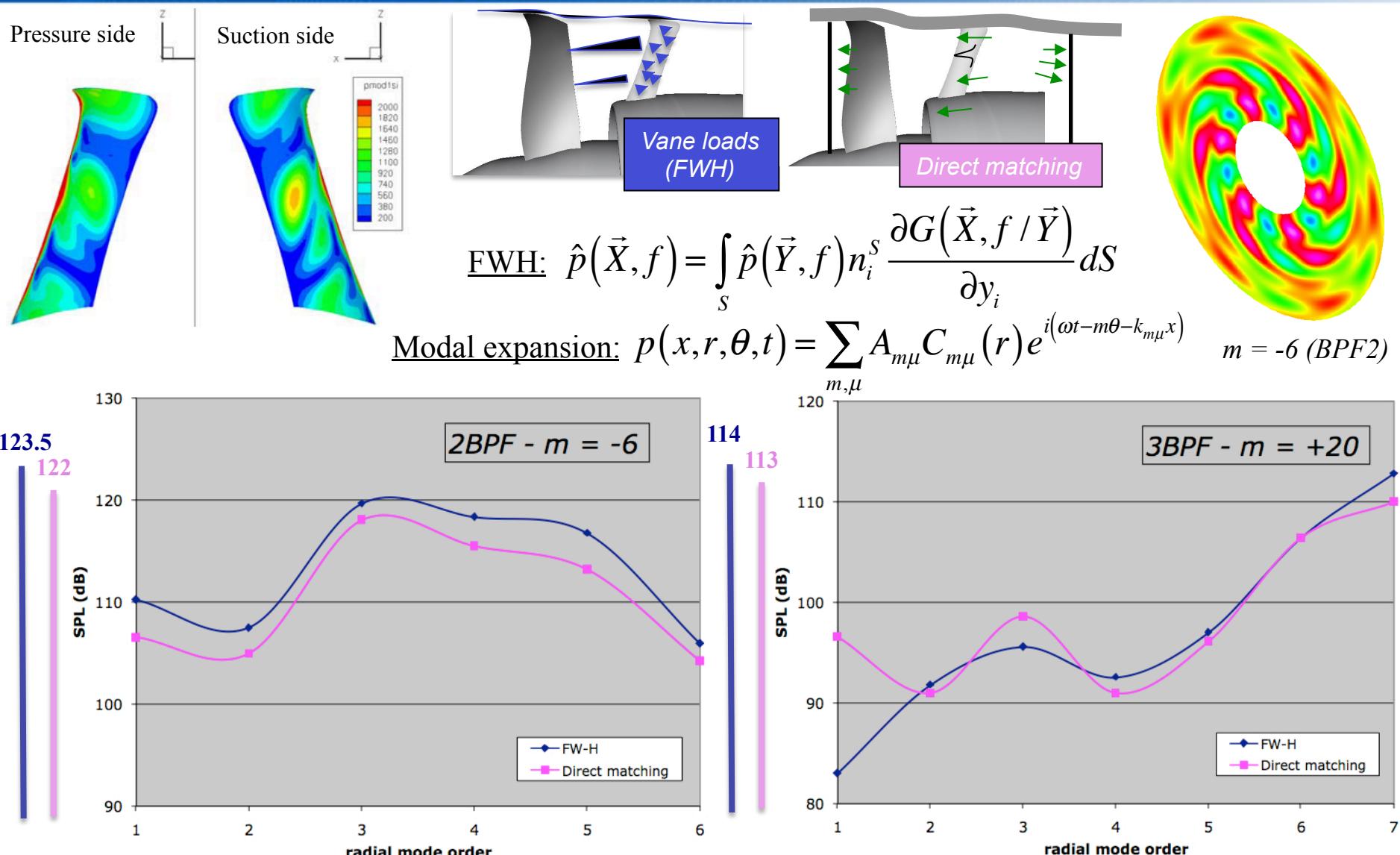
## *Zeppelin post-processing tool (R. Barrier)*



- *Unsteady pressure distribution (blade or vane)*  
=> *FWH solver (loading noise) inputs*
- *Angular mode spectrum over cross-sections*  
=> *Fourier-Bessel mode decomposition (CAA input)*
- *Harmonic disturbances over cross-sections*  
=> *Direct PWL (using Cantrell & Hart formulation)*

# URANS-based simulations for interaction noise (3)

In-duct (downstream) SPL calculations using FWH or direct approach



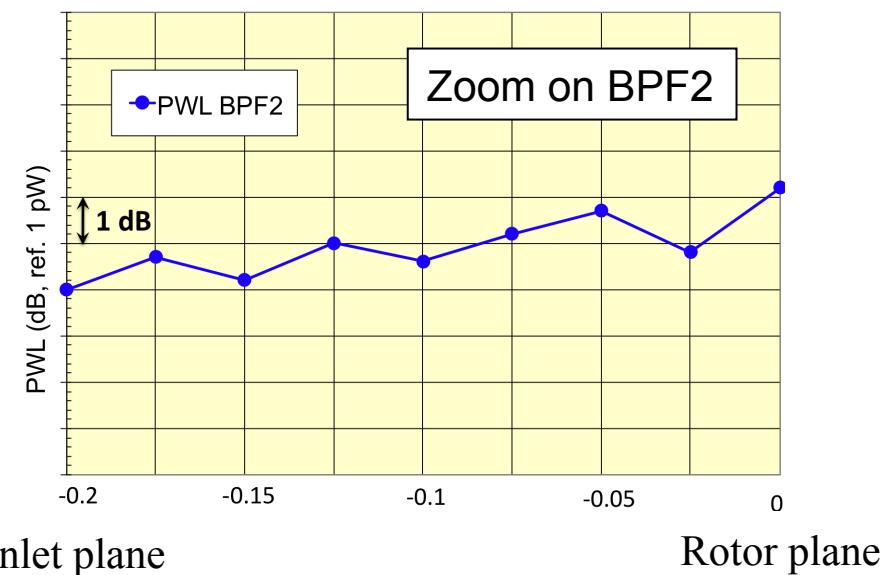
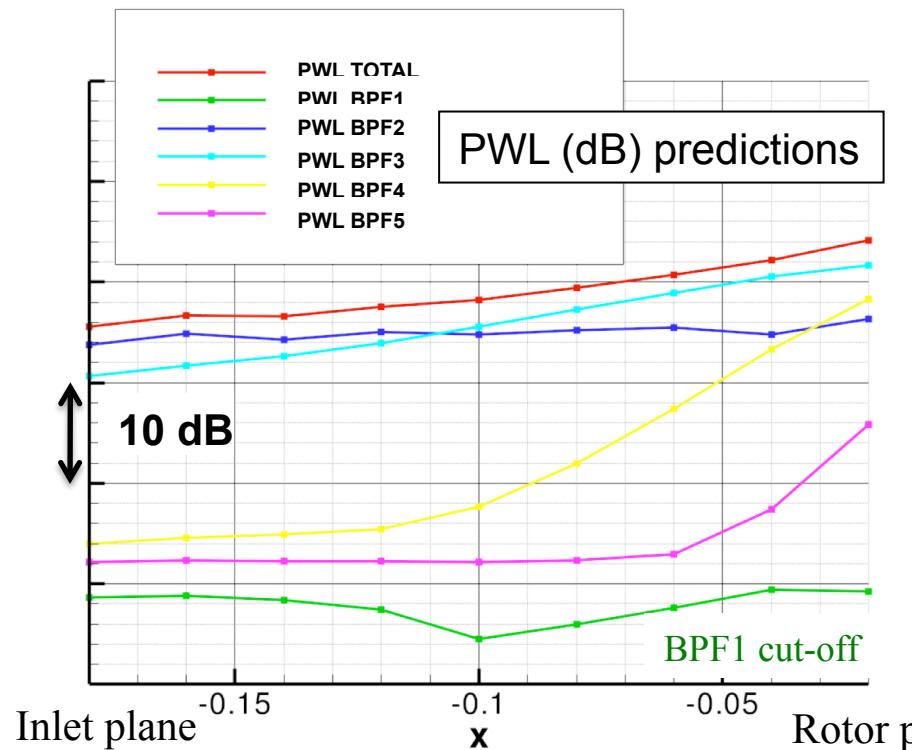
# URANS-based simulations for interaction noise (4)

Direct computation of PWL (upstream) using *ZeppeLin* (C&H formulation)

Cantrell & Hart:  $\bar{I}_x(f) = \frac{1}{2} \Re e \left\{ \left( 1 + M_x^2 \right) p(f) u_x^*(f) - M_x \left( \rho_0 c_0 u_x^2(f) + \frac{p^2(f)}{\rho_0 c_0} \right) \right\}$

(valid for irrotational flows)

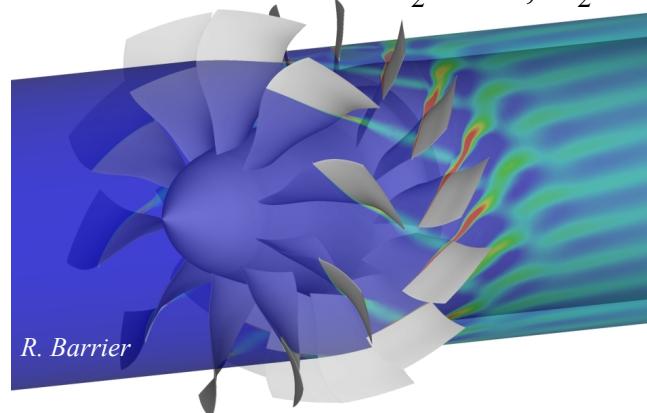
$$W_{direct}(f) = \int_{S_{duct}} \bar{I}_x(f) dS$$



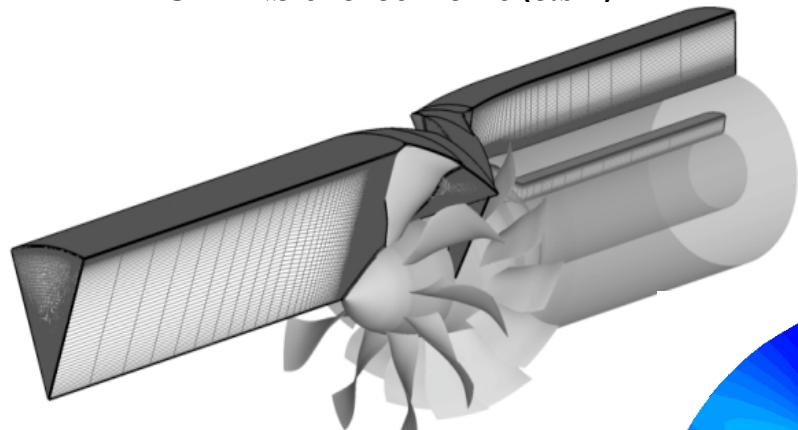
# Aeroacoustic simulations of a counter-rotating turbofan (1)

## CFD/CAA chaining (\*)

CRTF Snecma model:  $B_1 = 10$  ;  $N_1 = 77.5$  Hz  
 $B_2 = 14$  ;  $N_2 = 69.5$  Hz

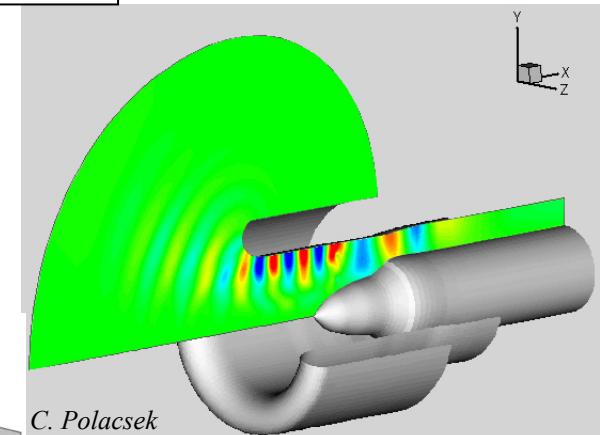
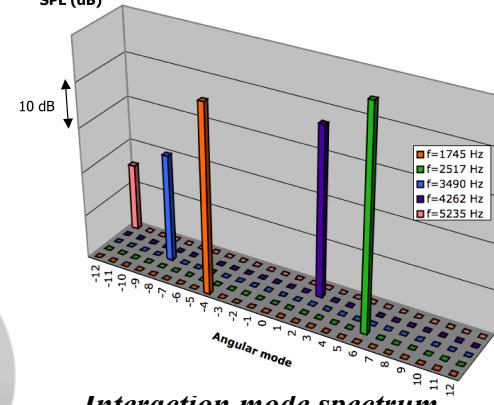
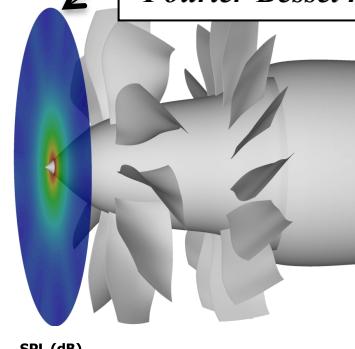


URANS chorochronic (*elsA*)



CFD 3D grid

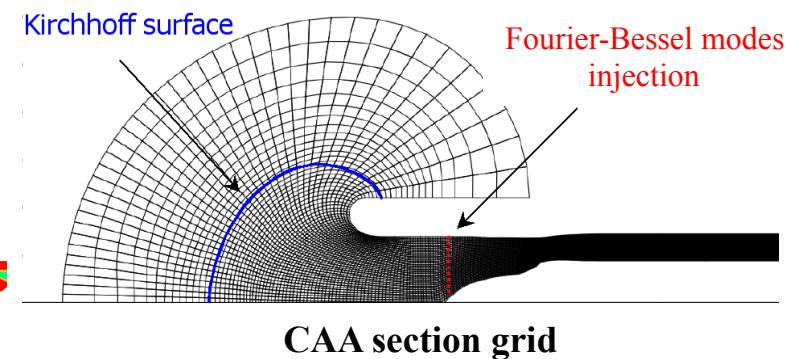
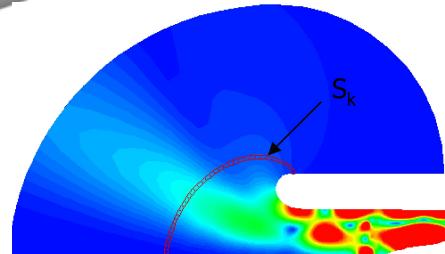
*CFD  $\Leftrightarrow$  CAA post-processing*  
*Fourier-Bessel mode expansion*



Hanson:

$$f_{12} = |n_1 B_1 N_1 + n_2 B_2 N_2|$$

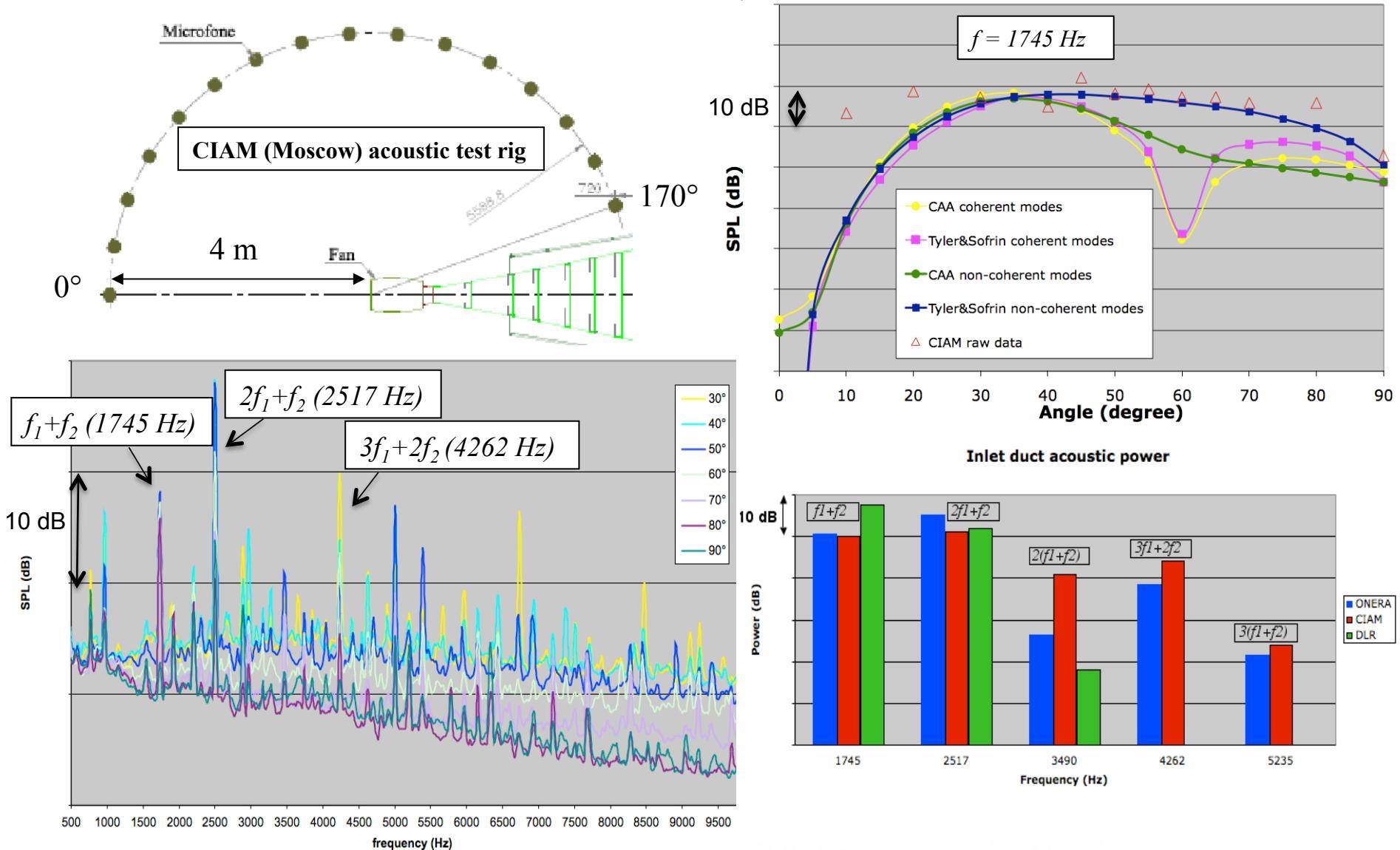
$$m = n_1 B_1 - n_2 B_2$$



10 (\*) C. Polacsek, R. Barrier, *Numerical simulation of counter-rotating fan aeroacoustics*, 13th AIAA/CEAS Conference, Roma (Italy), 2007.

# Aeroacoustic simulations of a counter-rotating turbofan (2)

## Acoustic predictions vs experiment



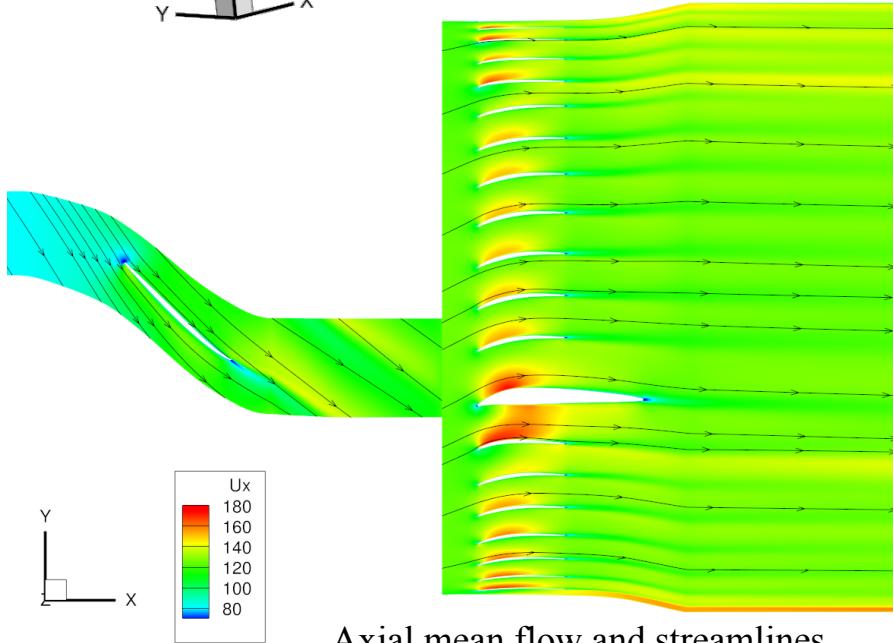
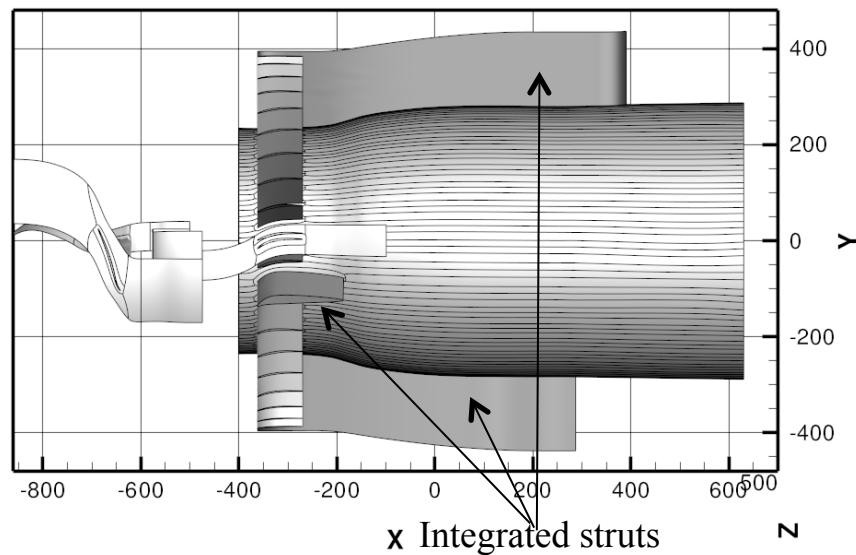
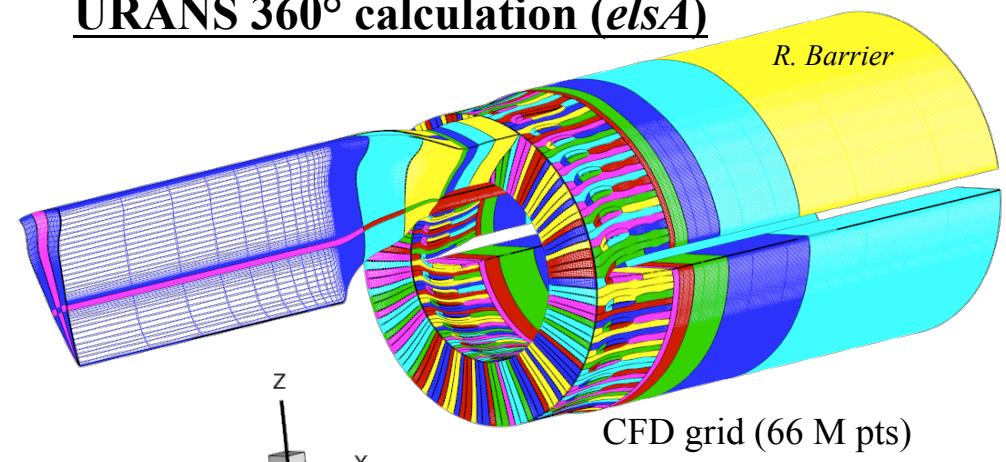
# Interaction noise simulations on a LEAP engine (1)

## Heterogeneous OGV and 360° URANS overviews

40 vanes non-axi OGV  
(including struts)

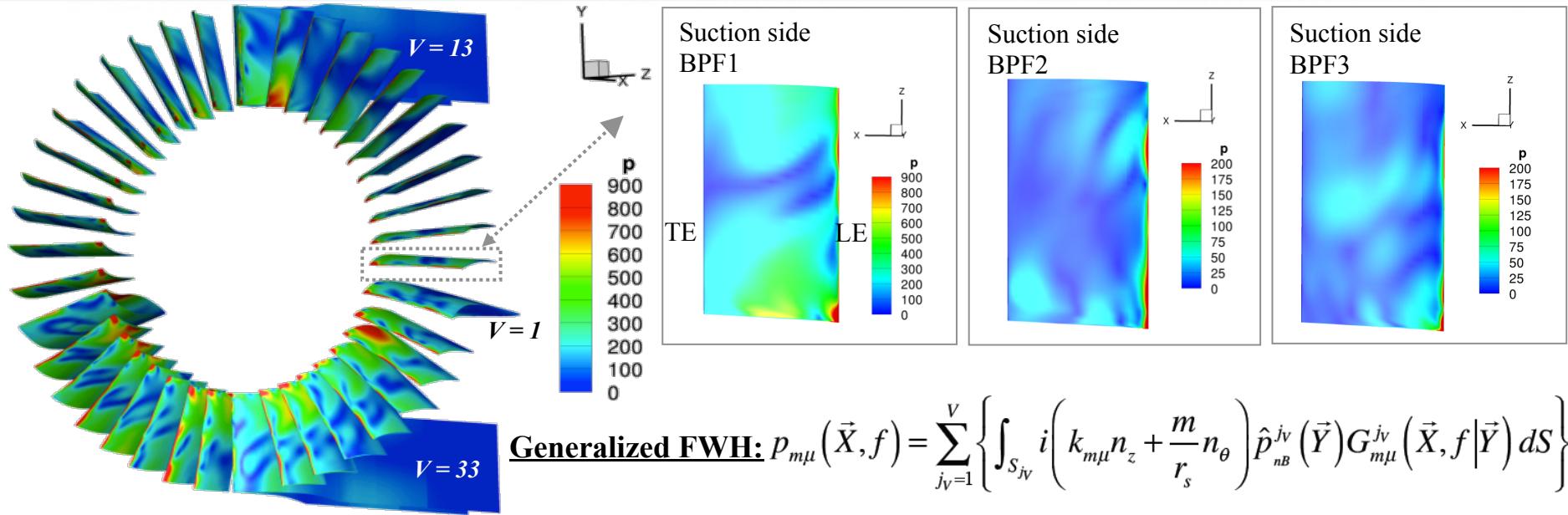


URANS 360° calculation (*elsA*)

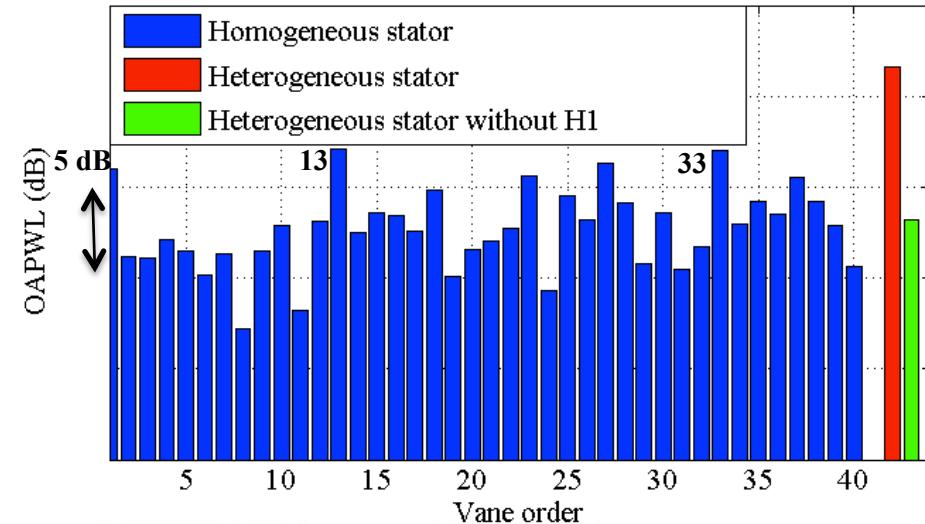
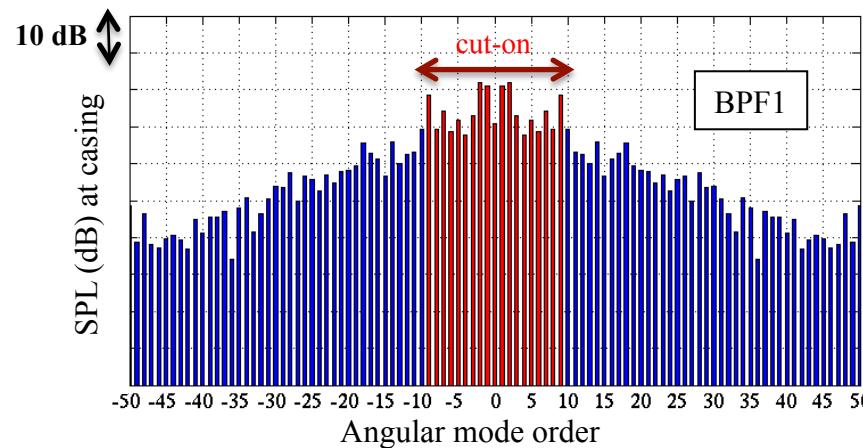


# Interaction noise simulations on a LEAP engine (2)

Vane loads analyzes and extended FWH predictions



$m = nB \pm k \Leftrightarrow$  all cut-on modes

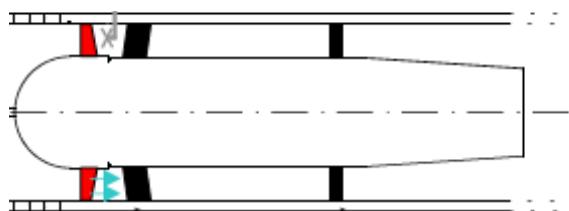


# Broadband noise simulations

# Rotor-stator broadband noise simulations using LES (1)

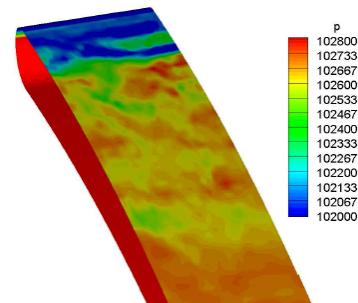
## Rotor-stator model (DLR) PROBAND project

Turbofan model in DLR rig



$B=16$ ;  $V=24$   
 $R_H/R_T = 0.613$   
 $N_{rot} = 3000 \text{ RPM}$   
 $M_x = 0.22$   
 $Re_c = 220,000$

Wall pressure snapshot  
(vane strip, suction side)



### 2.5D LES (*elsA*)

[*J. Riou et al., Inter-noise 2007*]

WALE subgrid scale model

1 blade/1 vane channel

Spanwise extent: 4.3 mm (0.1 chord)

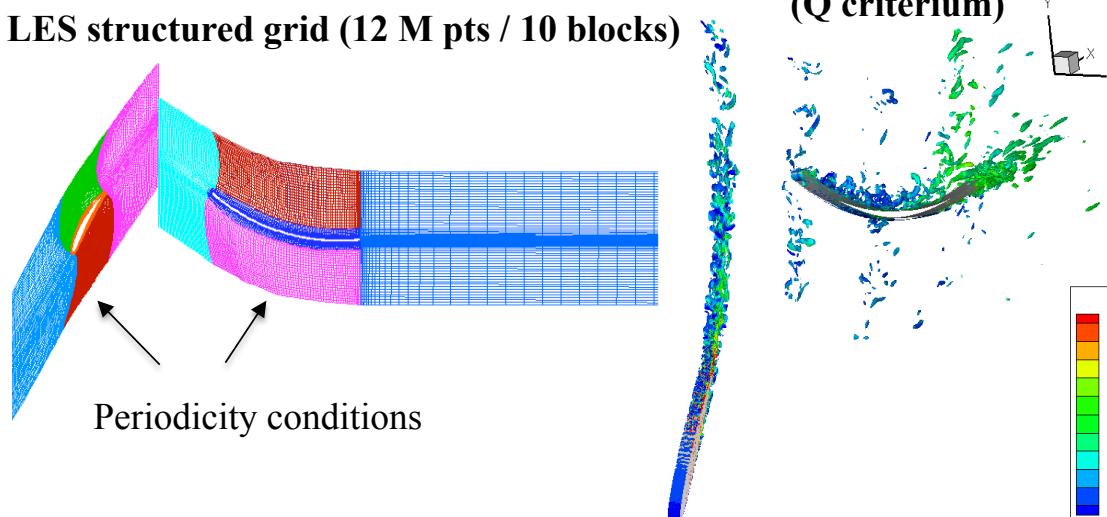
### Acoustics

[*G. Reboul et al., Inter-noise 2008*]

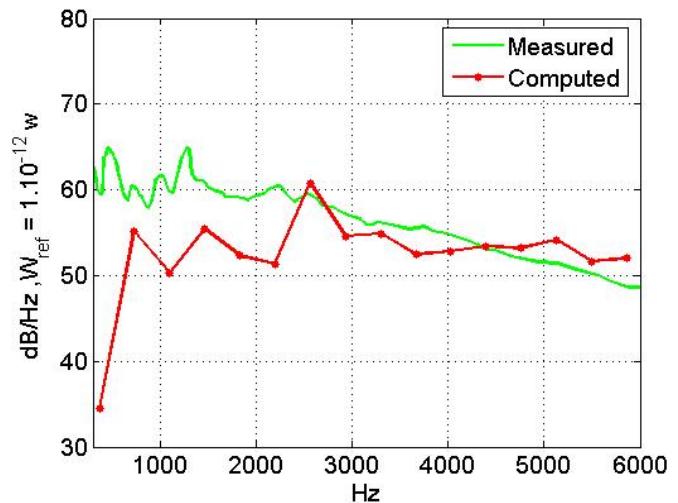
Unsteady vane pressure + FWH (in-duct)

$\Delta f = 250 \text{ Hz}$

LES structured grid (12 M pts / 10 blocks)

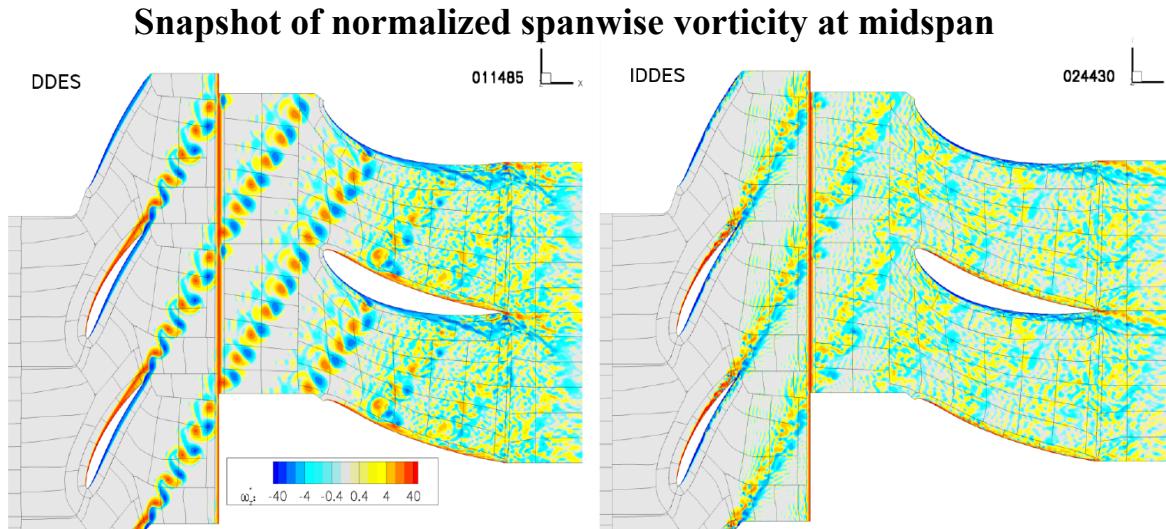


In-duct power density spectrum (dB/Hz)



# Rotor-stator broadband noise simulations using DES (2)

## Rotor-stator model (DLR) FLOCON project



$B = 24 ; V = 30$   
 $M_x = 0.22$   
 $Re_c = 220,000$

### 2.5D DES (ELAN TUB solver)

DDES "Delayed Detached Eddy Sim."

IDDES "Improved Delayed Detached ..."

[**B. Greschner & F. Thiele, AIAA-2011-2873**]

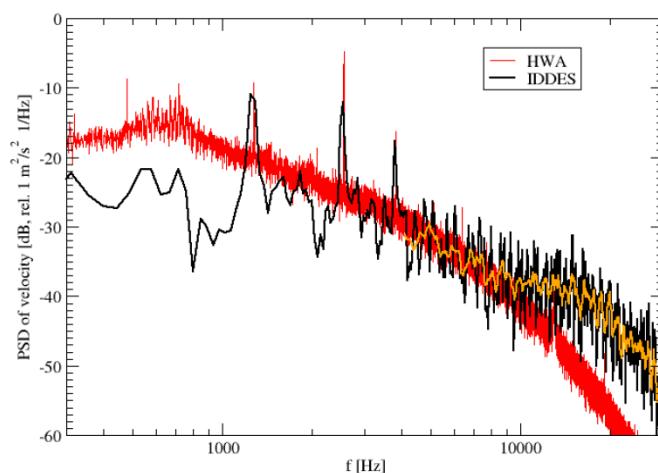
Structured grid : 14.5 M points / 154 blocks

1 blade/1 vane channel

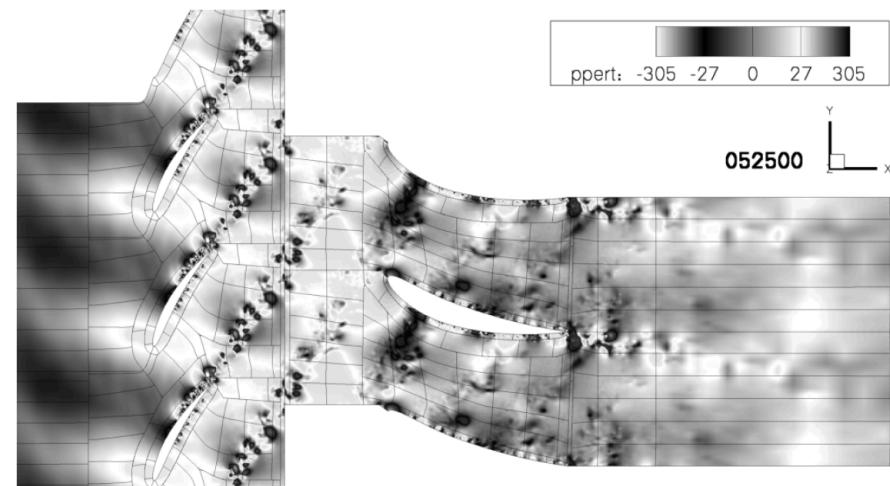
Spanwise extent: 15 mm (0.34 chord)

Periodic conditions in spanwise direction

**PSD (dB) of velocity at interstage plane**



**Snapshot of pressure perturbation (sound propagation)**



# Rotor-stator broadband noise simulations using LES (3)

## Single stage axial compressor model (CME<sub>2</sub>/LML)

$B = 24$ ;  $V = 30$   
 $R_H/R_T = 0.77$   
 $N_{rot} = 6300 \text{ RPM}$   
 $M_x = 0.33$

### Quasi 3D LES (*Turb'Flow ECL solver*)

[J. Laborderie, S. Moreau, A. Berry, AIAA-2013-2042]

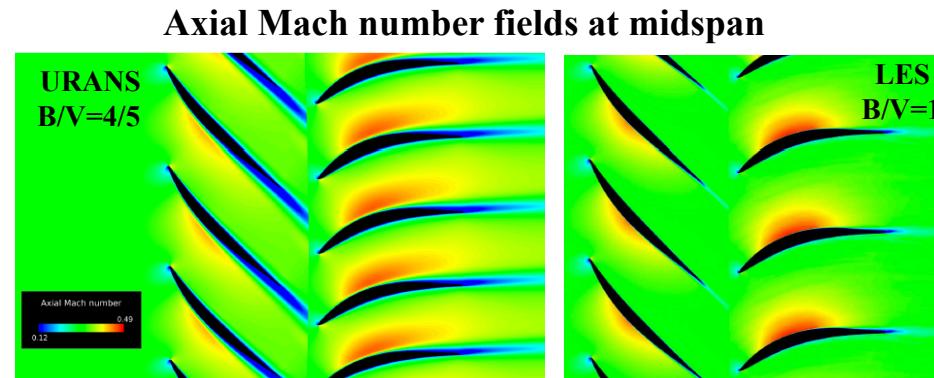
Shear-improved Smagorinsky model

Structured grid: 14 M points / 164 blocks

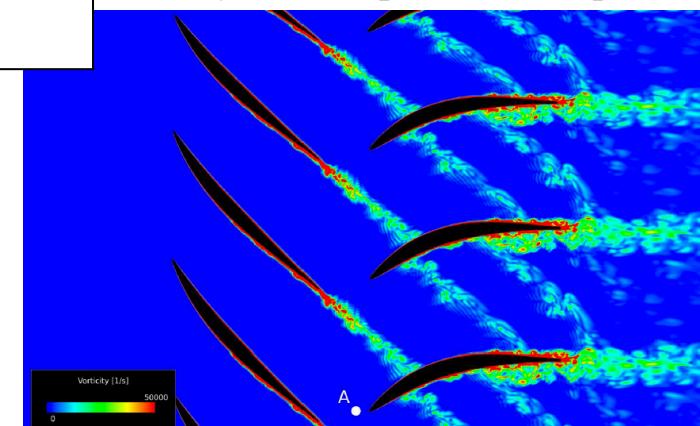
1 blade/1 vane channel

Spanwise extent: 1/3 full span

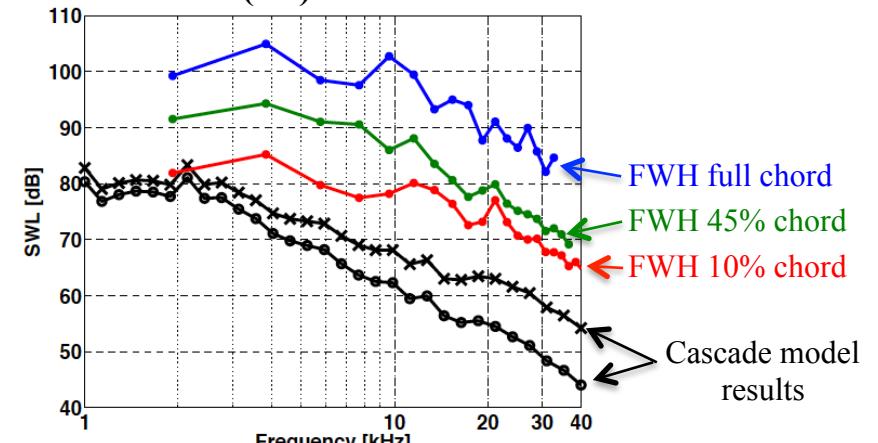
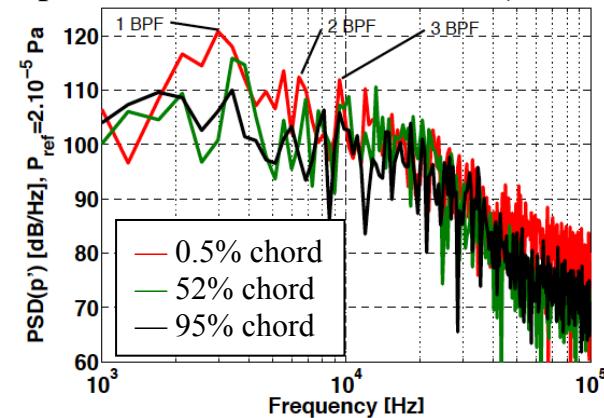
Vorticity field snapshot at midspan



Axial Mach number fields at midspan



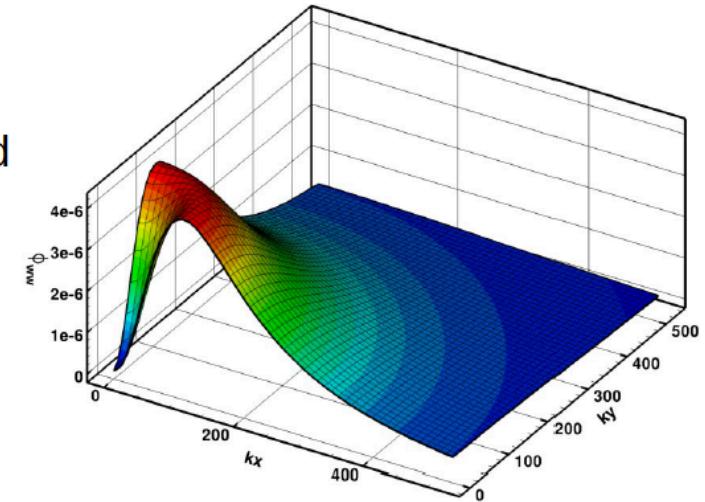
In-duct PWL (dB) downstream stator



# Turbulent wake injection in the CAA

## Stochastic model implemented in *sAbrinA*

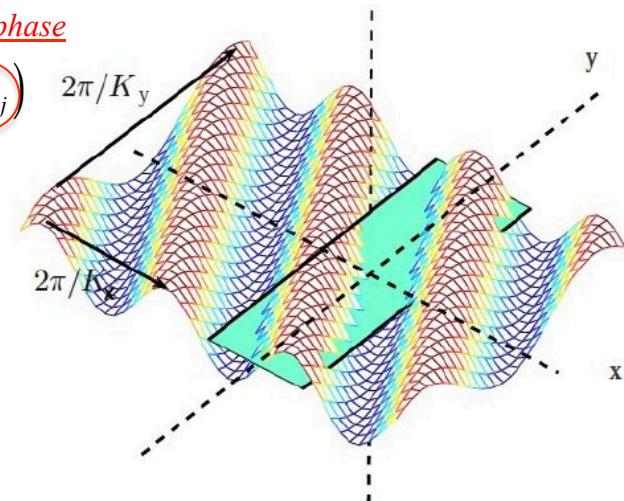
- Based on a Fourier modes decomposition of the incoming turbulent velocity (Kraichnan's HIT model)
- By analogy with Amiet's theory:
  - only the upwash velocity component ( $w'$ ) is modeled and injected
  - only the chordwise ( $k_x$ ) and spanwise ( $k_y$ ) wavenumbers are considered
- Modes amplitudes related to the HIT energy spectrum of the upwash velocity ( $\Phi_{ww}$ )



$$\begin{cases} u'(x,y,t) = v'(x,y,t) = 0 \\ w'(x,y,t) = \sum_{i=1}^N \sum_{j=-M}^M 2\sqrt{\Phi_{ww}(K_{x,i}, K_{y,j})} \Delta K_x \Delta K_y \cos(\omega_i t - K_{x,i}x - K_{y,j}y + \varphi_{i,j}) \end{cases}$$

*random phase*

- $\Phi_{ww}$  is the 2-wavenumbers spectrum adjusted using 2 parameters: turbulent intensity  $Tl$  and integral length scale  $\Lambda$
- Taylor's frozen turbulence hypothesis:  $\omega = k_x U_0$
- Divergence-free condition satisfied:  $\nabla \cdot \vec{u} = 0$

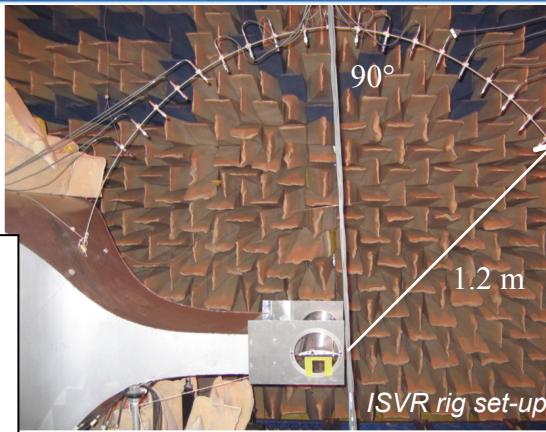


# Broadband interaction noise using CAA (1)

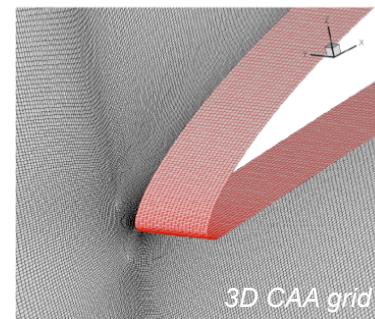
Turbulence-airfoil case – ISVR configuration (\*)



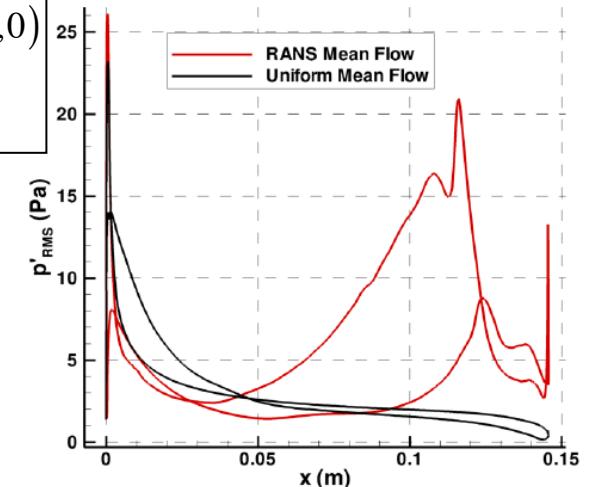
NACA 651210  
 $U_0 = 60 \text{ m/s}$   
 Chord = 150 mm  
 Span = 450 mm  
 $T_I = 2.5\%$   
 $\Lambda = 6 \text{ mm}$



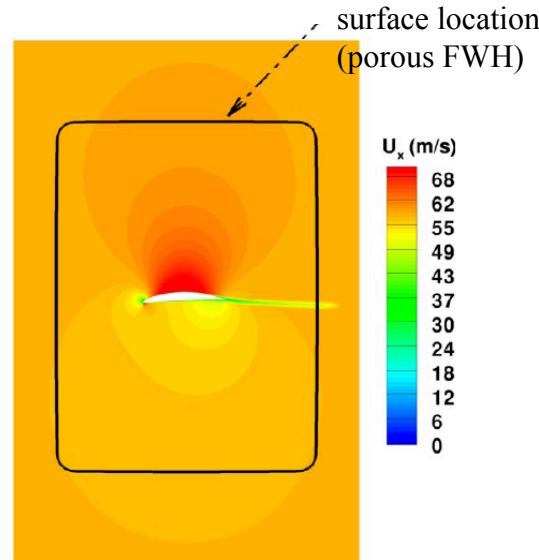
CAA grid : 8.3 M points  
 Von-Karman model:  $\phi_{ww}(K_x, 0)$   
 $f_{max} = 5 \text{ kHz}$ ;  $\Delta f = 100 \text{ Hz}$   
 Spanwise extent: 10 mm



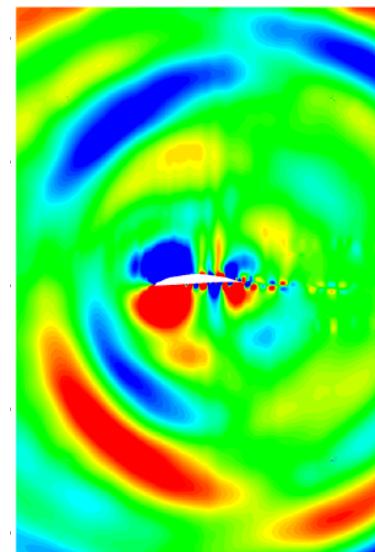
## CAA chordwise RMS presssure



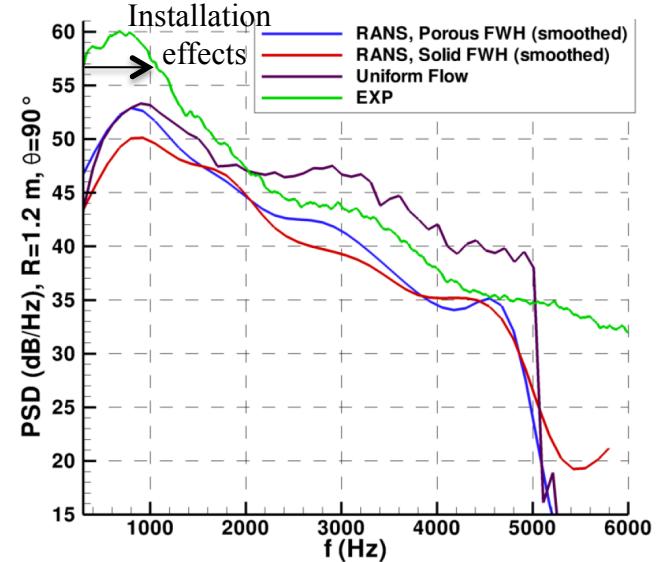
## Axial mean flow (RANS/elsA – CERFACS)



## Pressure disturbance snapshot

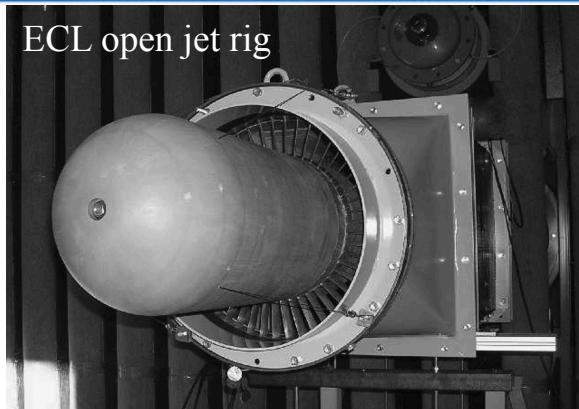


## PSD comparisons (90° microphone)



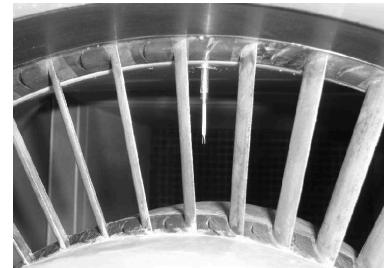
# Broadband interaction noise using CAA (2)

Turbulence-annular grid case - ECL configuration (\*)

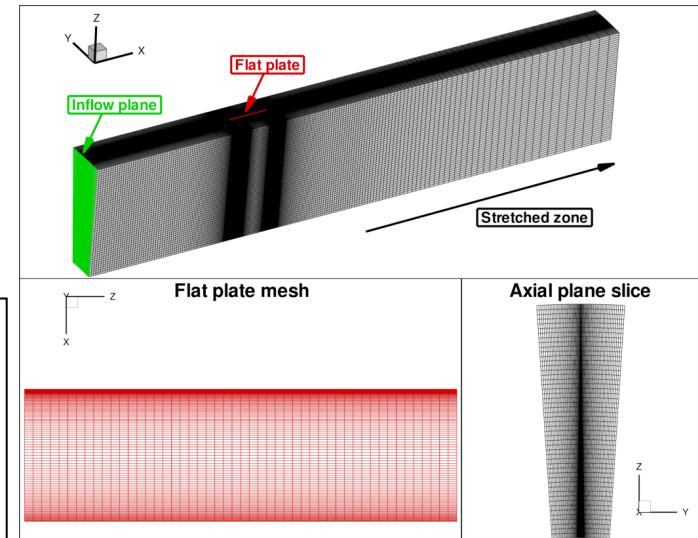


$$\begin{aligned} V &= 49 \\ U_0 &= 80 \text{ m/s} \\ T_I &= 6\% ; \Lambda = 20 \text{ mm} \end{aligned}$$

Annular flat plate grid

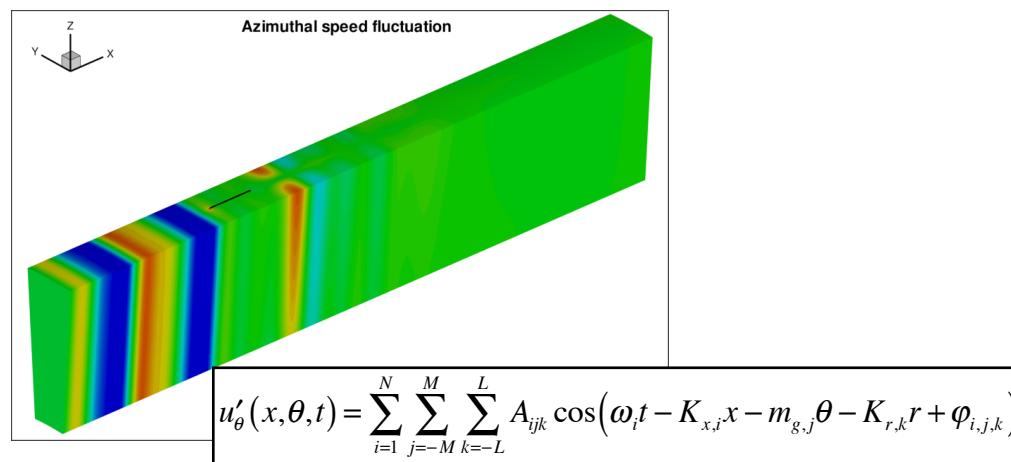


CAA grids & computation domains

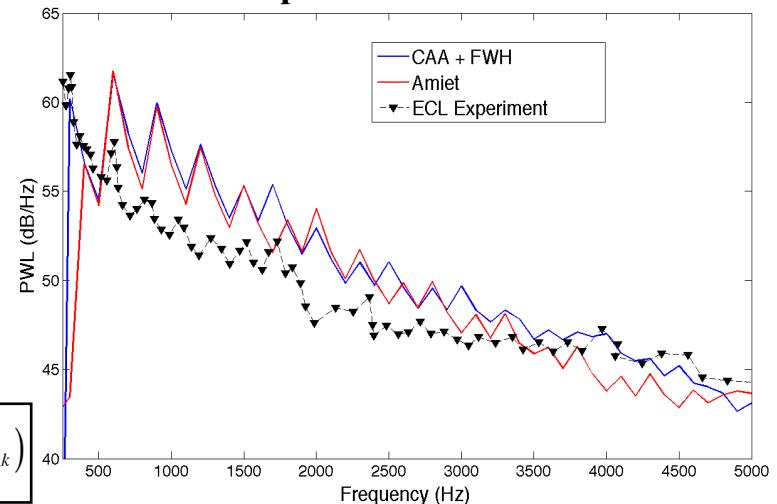


CAA grid : 1.5 M points  
 Liepmann spectrum model:  $\phi_{ww}(K_x, 0)$   
 $f_{max} = 5 \text{ kHz} ; \Delta f = 100 \text{ Hz}$   
 1 vane channel ( $\Rightarrow$  no modes  $m_g$ )  
 Angular periodicity conditions

Snapshot of randomized velocity disturbance  
 (tangential component /  $K_x$  wave number only)



In-duct PWL spectra downstream the stator



## Challenges & perspectives (non-exhaustive list)

- High-order schemes implementing in CFD (eIsA)
  - *Curvilinear compact scheme using high order interpolation (Cerfacs)*
  - *RBC (Residual Based Compact) schemes (Simunef)*
- Adapted rotor-stator interface for LES turbomachinery applications (*PhD thesis*)
- DES techniques to assess 3D turbulent fields on industrial configs (*ZDES simulation of a full rotor blade on LEAP engine*)
- Extension of stochastic/CAA methodology on rotor-stator configs (*PhD thesis*)
- Different coupling strategies between CFD and CAA under study  
*NRI (Non-Reflecting Interface) method implemented in sAbriNA code*
- Integration & applications of Lattice Boltzman Method (*LaBS code*)

# THANKS FOR YOUR ATTENTION !

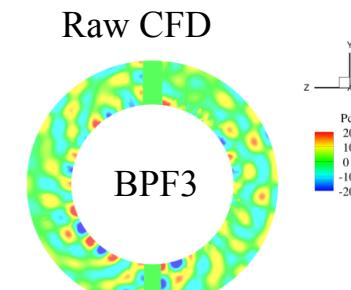
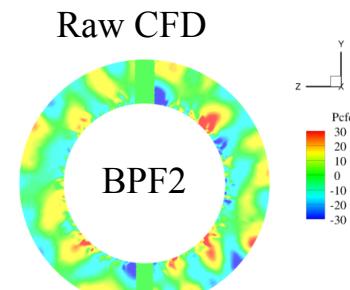
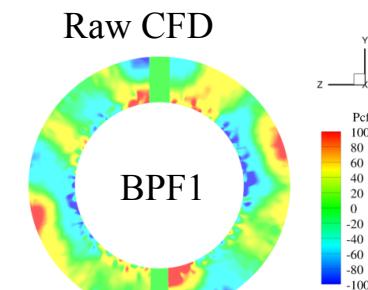
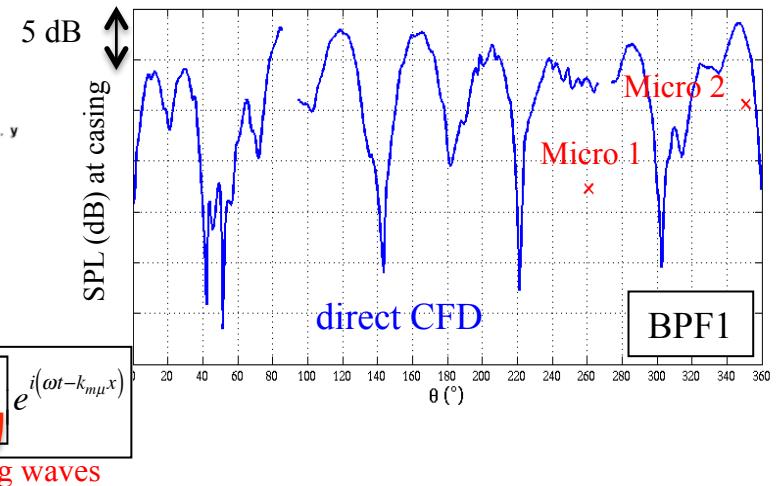
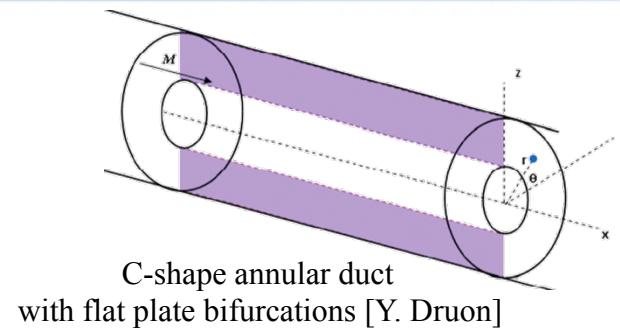
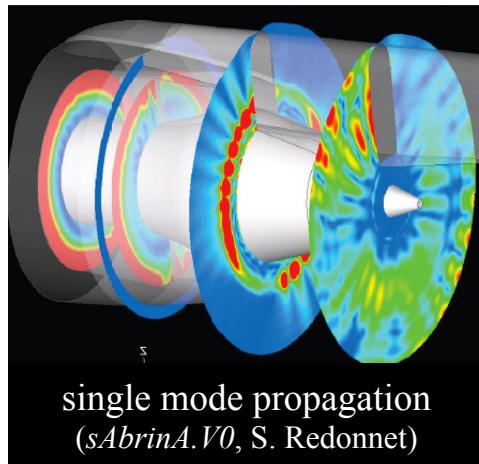


QUESTIONS ?

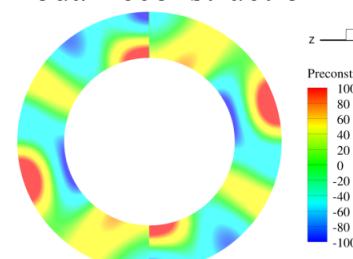


# Interaction noise simulations on a LEAP engine (3)

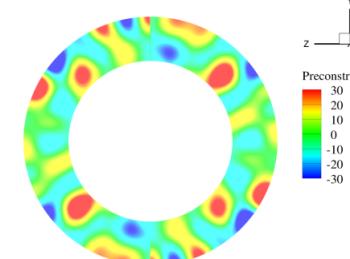
Propagation/pylones effects and SPL + PWL predictions



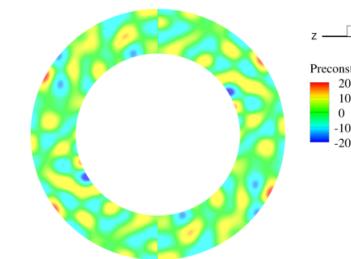
Modal reconstruction



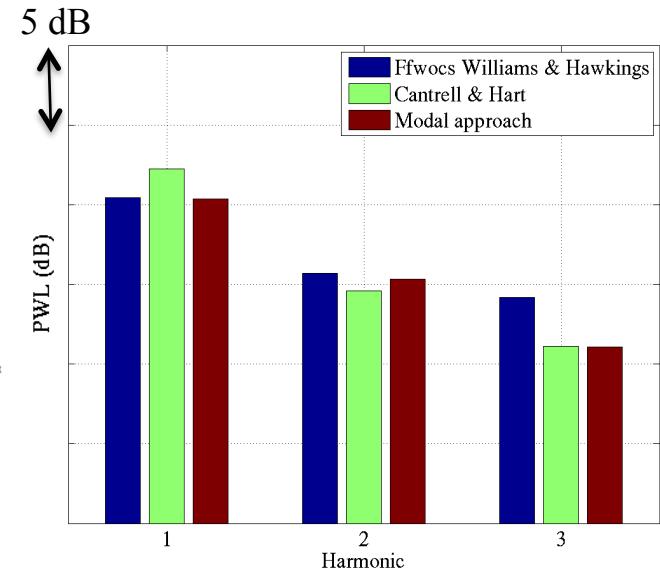
Modal reconstruction



Modal reconstruction



Amplitude of pressure harmonics



# Turbulent wake injection in CAA (1)

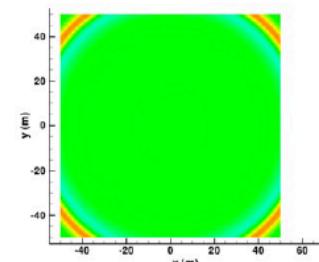
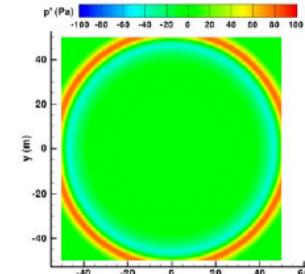
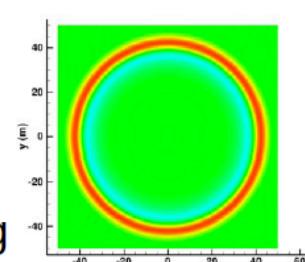
Tam's BC implementing in *sAbrinA* code

➤ *sAbrinA.v0* main characteristics:

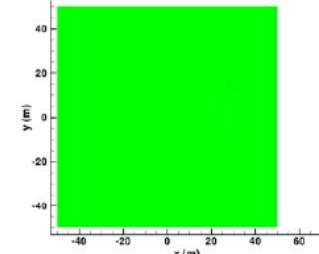
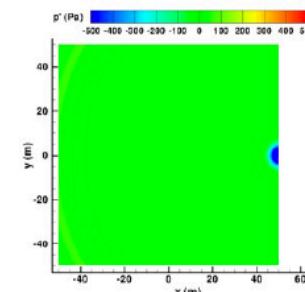
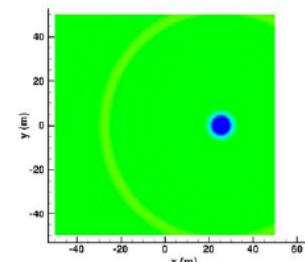
- nonlinear Euler equations in the time domain, on the conservative variables and written on the perturbations
- mean flows: uniform or RANS calculation
- 6<sup>th</sup> order finite difference spatial derivation scheme, 10<sup>th</sup> order filter, 3<sup>rd</sup> order Runge-Kutta time marching scheme
- multi-block structured curvilinear grids (parallelized using the MPI library)

➤ Tam's boundary conditions:

- outflow condition: adapted for hydrodynamic and acoustic outgoing waves
- inflow condition: allows the imposition of incoming perturbations



Exit of an acoustic monopolar pulse

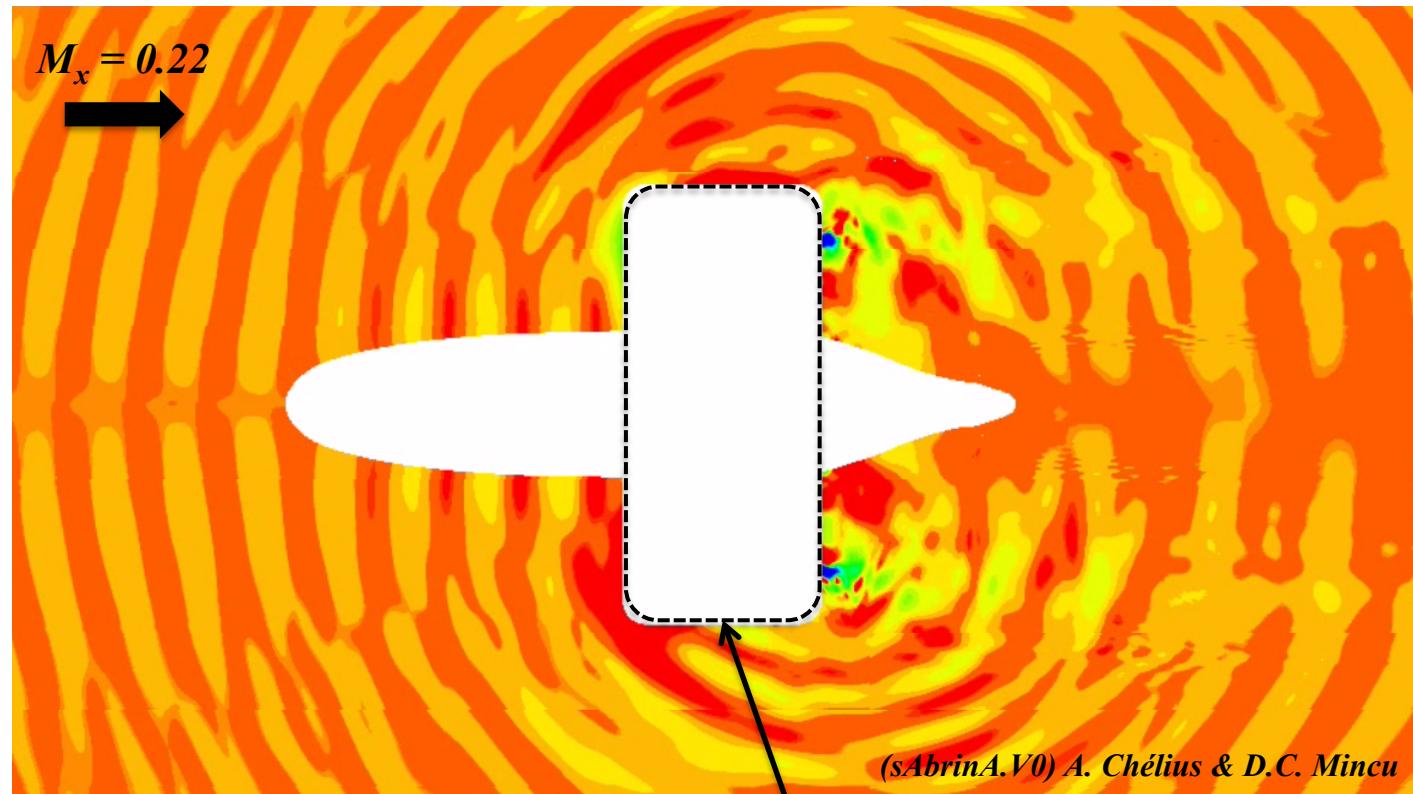


Exit of a vortex

# CFD-CAA chaining on CROR configuration

Application to AIPX7 (11x9-bladed pusher CROR) at take-off operating point

CAA sound pressure snapshot (section view) in RANS mean flow



Disturbance fields ( $\rho, p, u$ ) injection issued  
from URANS (*elsA*) chorochronic computation

