Turboengine noise prediction: present and future

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Background

Ventilation systems (cockpit, cargo)

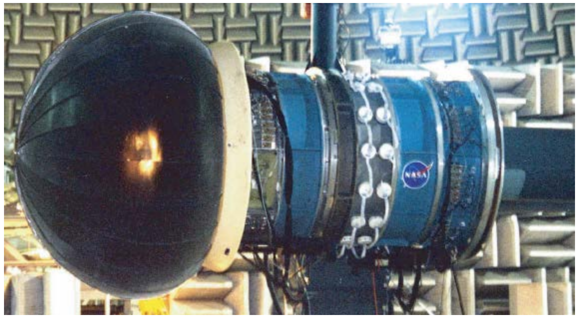
- Fan alone or rotor-stator stage
- Low to high Mach and Reynolds numbers
- Low number of blades
- Regulations more and more stringent

Propulsion systems (turboengines)

- Rotor-stator or rotor-rotor stage
- High Mach and Reynolds numbers
- High solidity
- Dominant noise at approach: soon to be the main source always (UHBR)

NASA ANCF test case

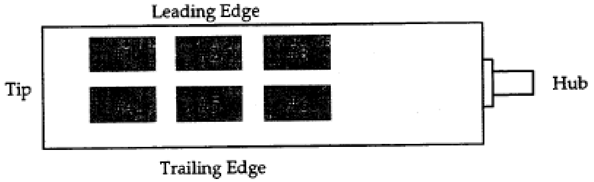
[1] Alan R.D. Curtis. Active control of fan noise by vane actuators. Technical Report NASA/CR–1999-209156, NASA, Glenn Research Center, May 1999.

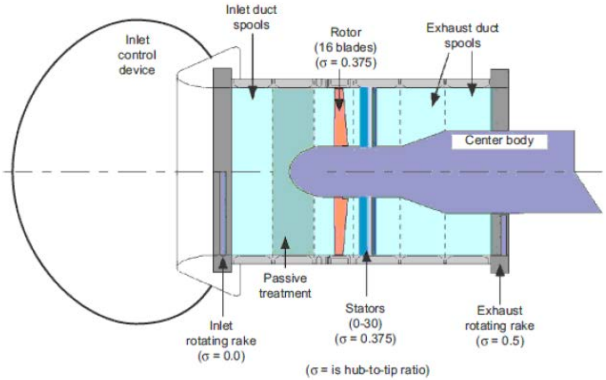


- Up to 28 stators, 168 actuators
- Upstream and downstream rings of sensors

[2] Daniel L. Sutliff. The Advanced Noise Control Fan. Technical Report NASA/TM—2006-214368, NASA, Glenn Research Center, Cleveland, Ohio

Thunder

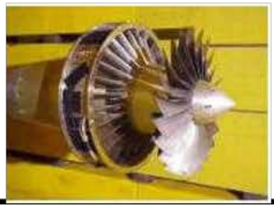




Excellent test case for tonal noise: directivities, modal decomposition for several stators
Instrumented blades
Results of active control with actuators on stator

NASA SDT test case

- Model of a modern turbofan bypass stage
- 22-inch (56 cm) diameter
- Hub-to-tip ratio = 0.5
- 22 blade rotor
- Several stator geometries
- Rotor speed: 7810 rpm

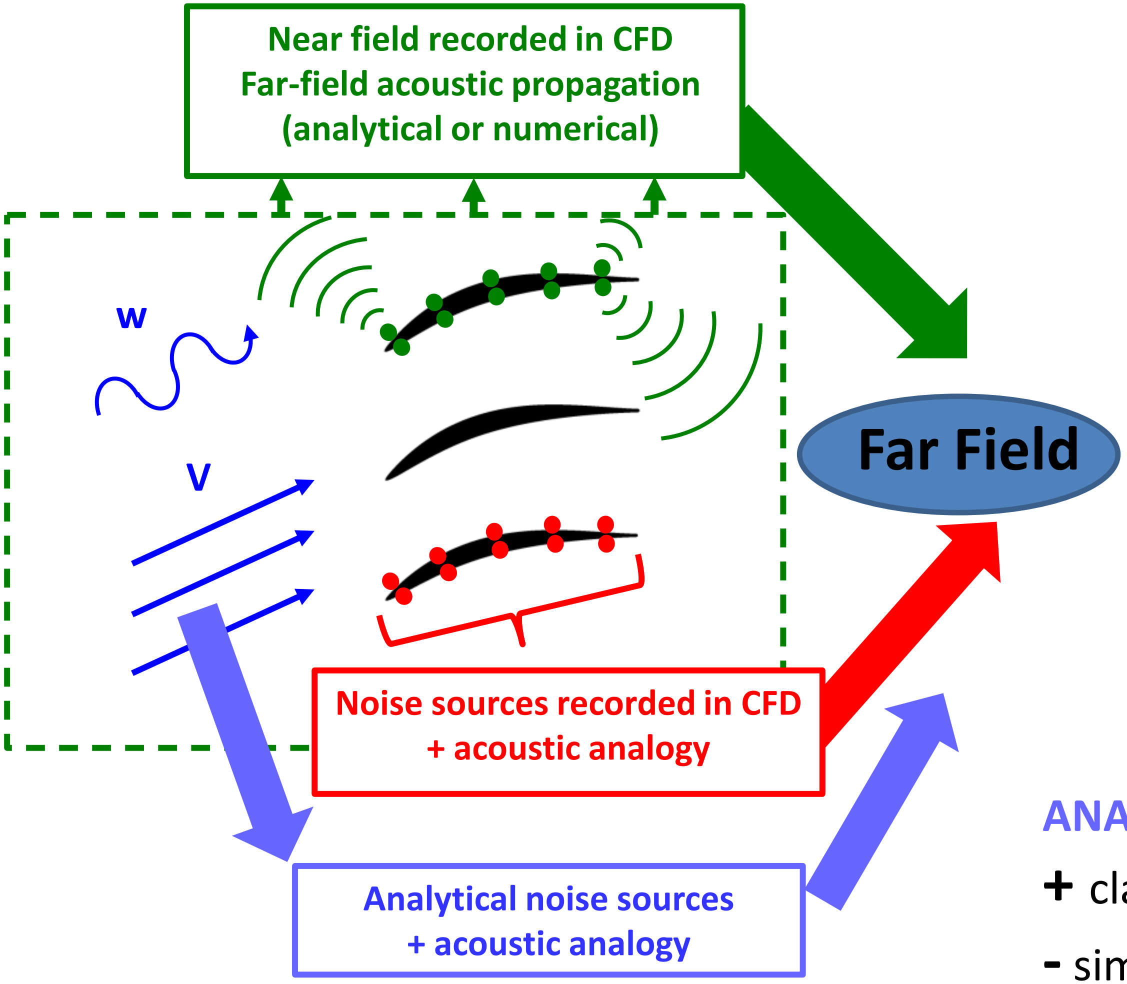
OGV	Operating conditions	Approach	Cut-Back	Take-Off
54 vanes (baseline)				
26 vanes				
26 swept vanes				

Fully available input data for running the model

Partially available input data for running the model

Unique broadband noise test-case (AIAA benchmark RC1-RC2)

Methods for fan noise prediction



DIRECT approach

+ actual acoustic propagation

- high-order schemes

HYBRID approach

+ classical CFD solvers (even incompressible)

+ complex source geometries

- No feedback mechanisms

- Hypothesis on the propagation (no complex installation effects)

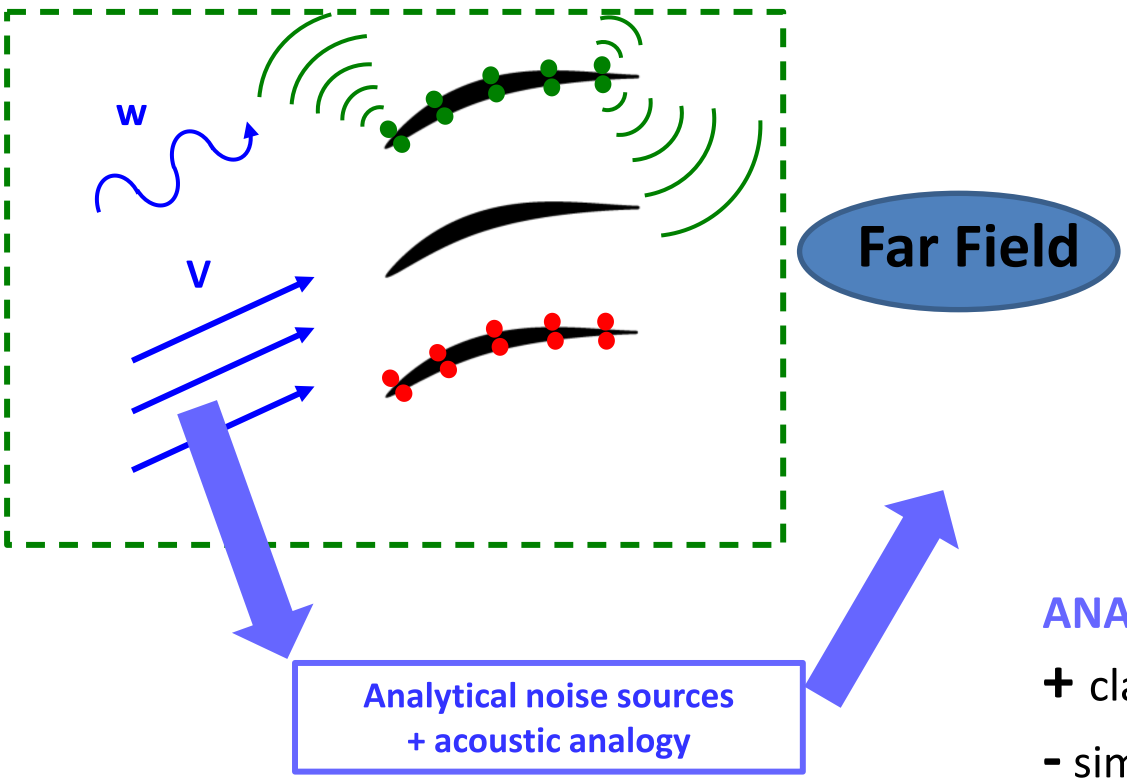
ANALYTICAL approach

+ classical CFD solvers (even RANS)

- simple source mechanism and geometry

Wang et al., ARFM 2006

Analytical methods for fan noise prediction



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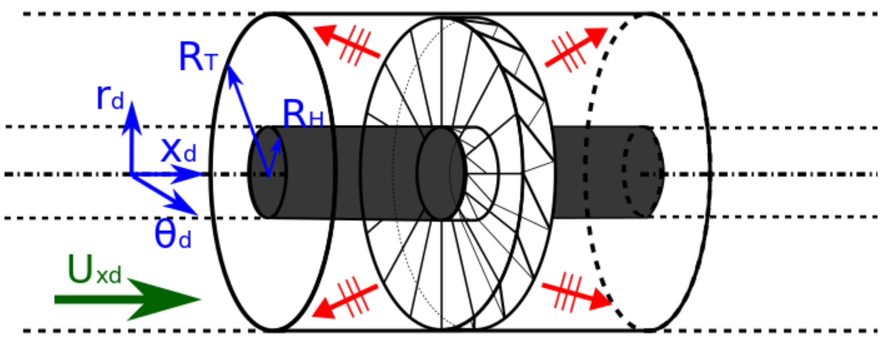
Analytical model of noise radiation

Configuration

- Infinite annular duct

Strip Theory

- Blade geometry describe by stacked strips
- Uniform axial flow/ strip



Acoustic analogy[1]

- Sources are generated by the flow
- No acoustic feedback on sources
- G : Green's function tailored to problem

- Quadrupolar term neglected
- Viscous forces neglected
- Monopolar source omitted

$$p(\mathbf{x},t) = \int_{-T}^{+T} \int_{S_p(t_0)} \frac{\partial G(\mathbf{x},t \mid \mathbf{x}_0,t_0)}{\partial x_{0i}} f_i \, dS(\mathbf{x}_0) \mathrm{d}t_0$$

Acoustic Sources: pressure fluctuations f_i on the blades

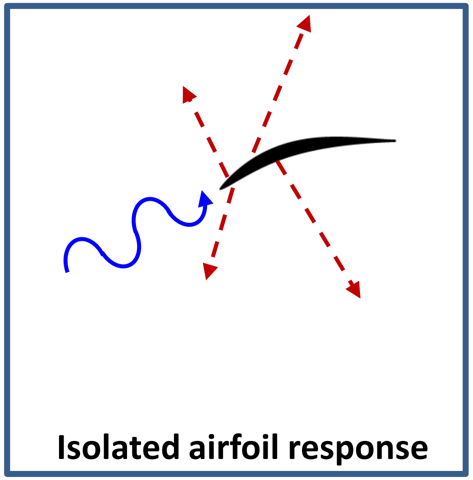
1 : Goldstein, 1976

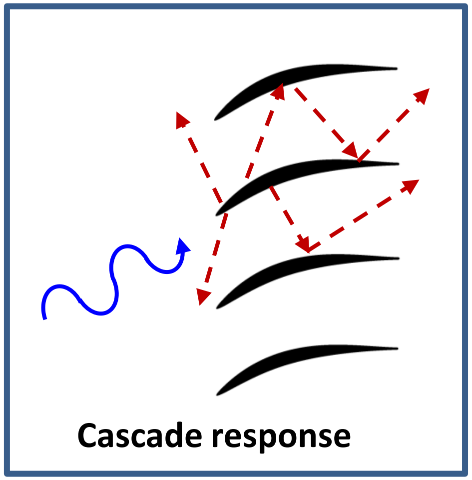
Posson et al., JSV 2010, 2011

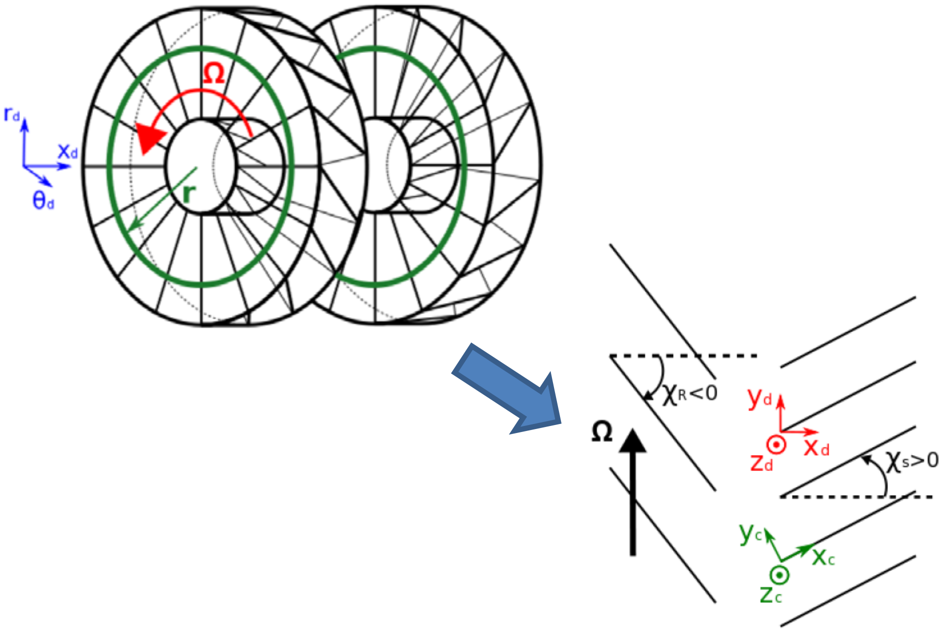
Analytical model of unsteady loading

Strip theory (except mode matching)

- Stage unwrap at each radius
- 2D profiles or rectilinear cascades
- Infinite flat plates **w/o thickness, camber**
- Mean **inviscid** flow parallel to flat plate
- **Kutta condition** at trailing edge

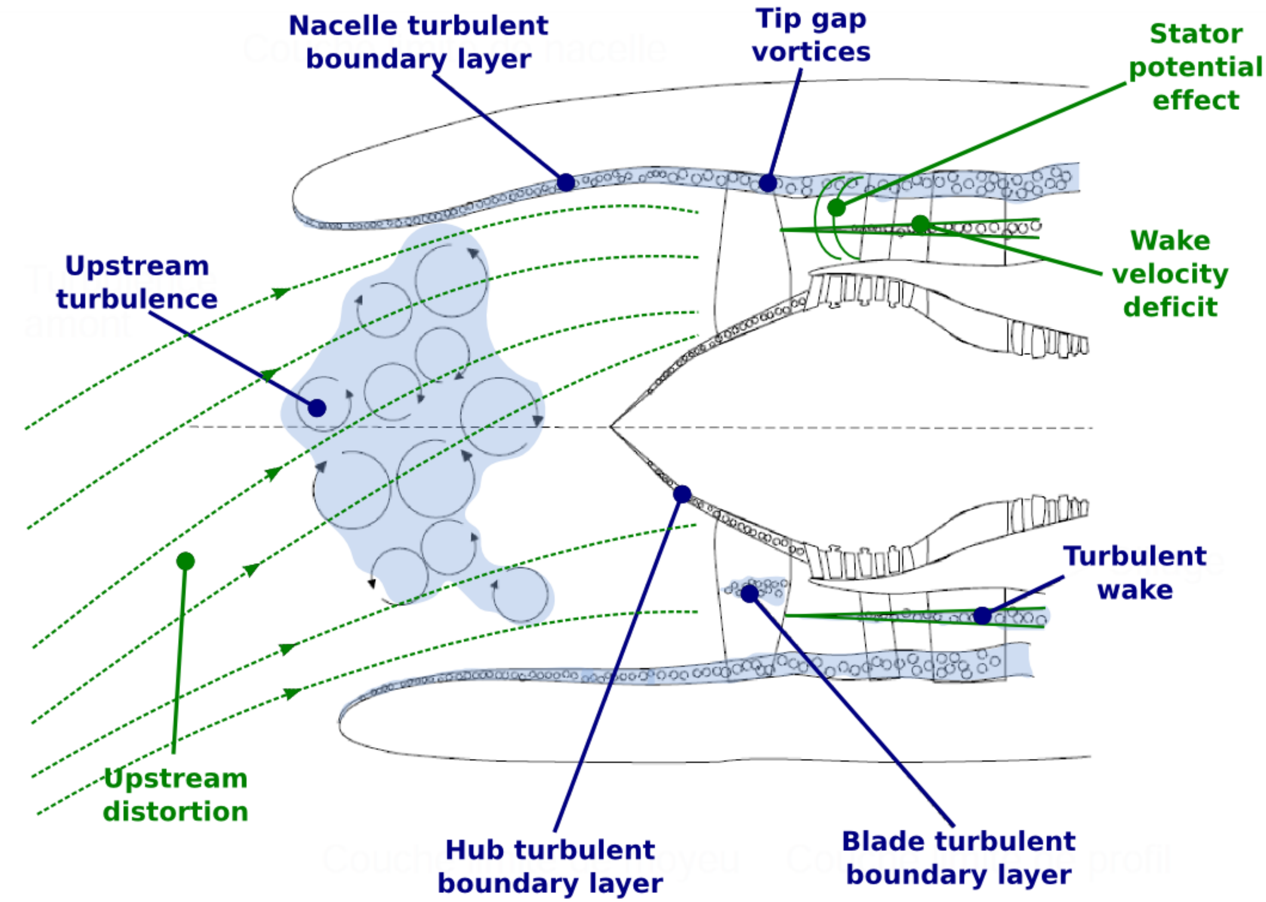






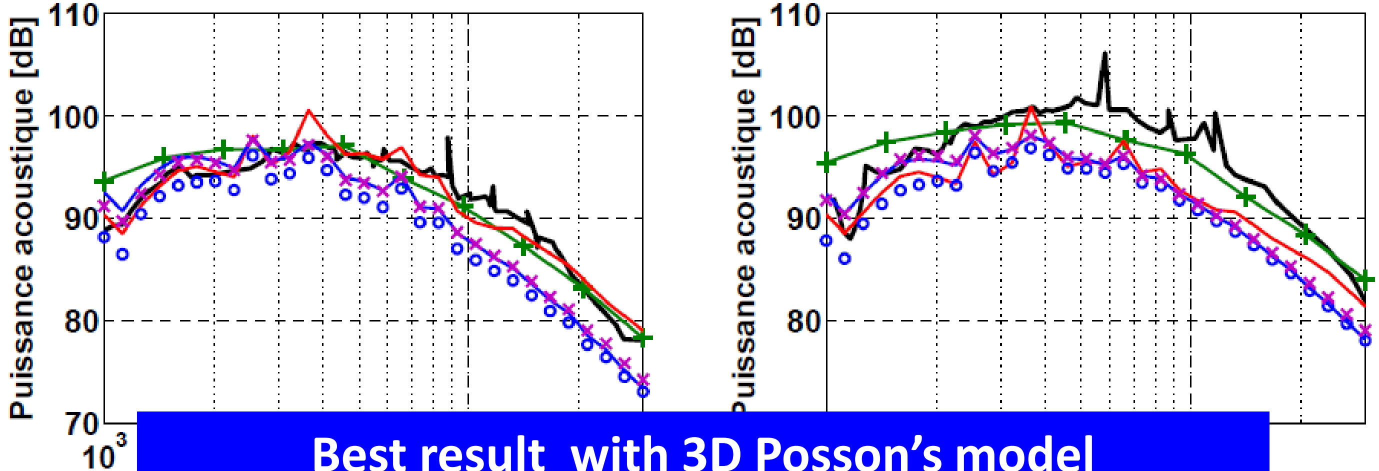
- **Low solidity: isolated profile**
  Unsteady lift computed using Schwarzchild theorem or Wiener-Hopf theory
  Roger & Moreau, IJA 2010
- **High solidity: cascade effect**
  (Influence on neighboring blade on blade response)
  Unsteady lift computed using Wiener-Hopf theory (*3D rectilinear cascade*)
  Posson et al., JFM 2010

Noise sources in axial turbomachine



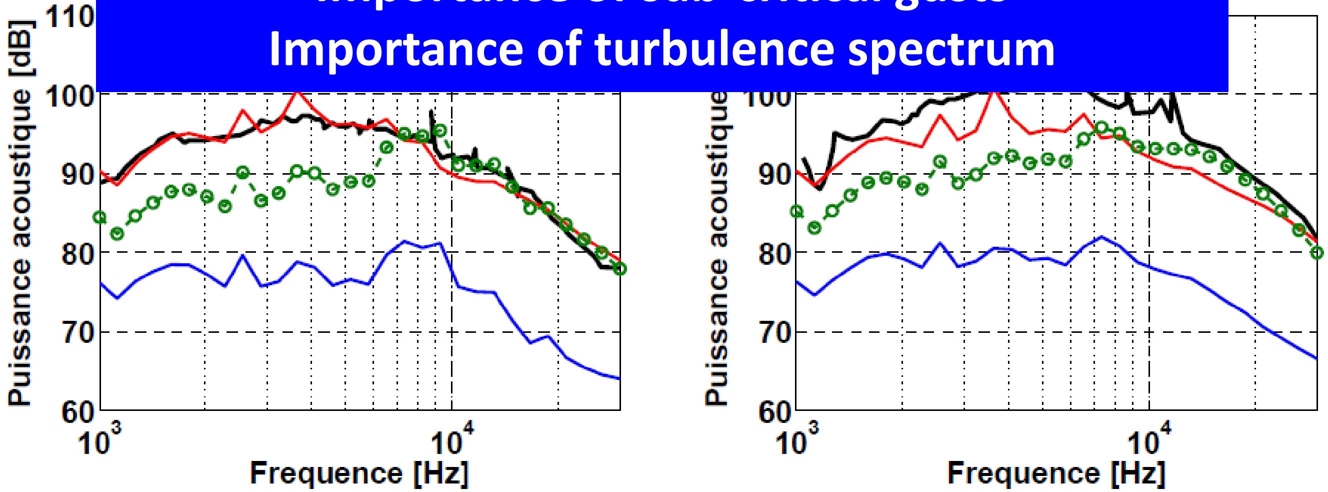
- **Upstream distortion/turbulence**: asymmetry of the inlet flow, flow detachment, duct junctions, protection grids...
- **Potential sources**: struts, any asymmetry in the geometry
- **Other sources:** vortex shedding (blunt trailing edge), boundary layer detachment

Results on SDT reference case



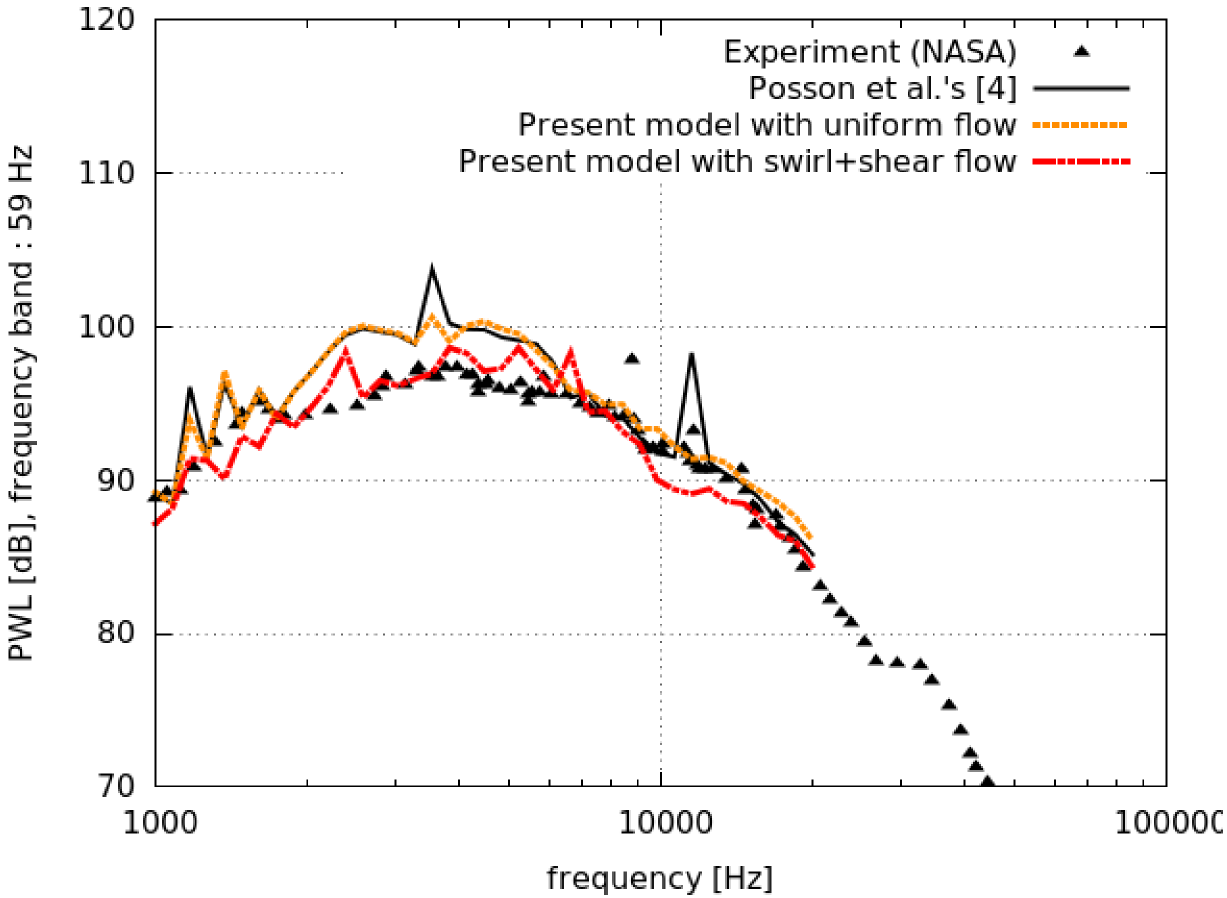
Best result with 3D Posson's model
Importance of 3D oblique gusts
Importance of 3D cascade response
Importance of sub-critical gusts
Importance of turbulence spectrum

Red: Posson; **Green**: Hanson … out sub-critical gusts ; **Violet:** Isolated profil…



Red: 3D Posson model; **Vert**: 2D Ventres response+ turbulence spectrum of Nallasamy-Envia;
Blue: Ventres response 2D + turbulence spectrum of Liepmann

Extension of BBN model with swirl

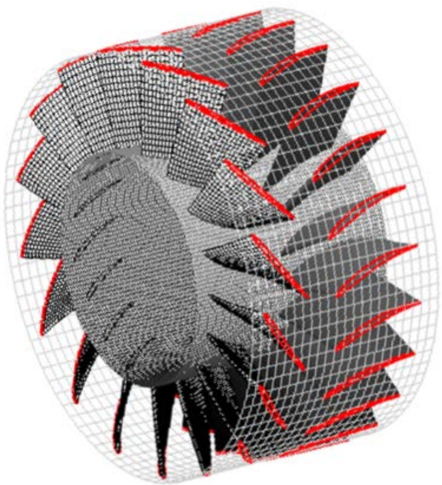


Significant effect of swirl in the low-mid frequency range
On-going effort to include interstage liner effect

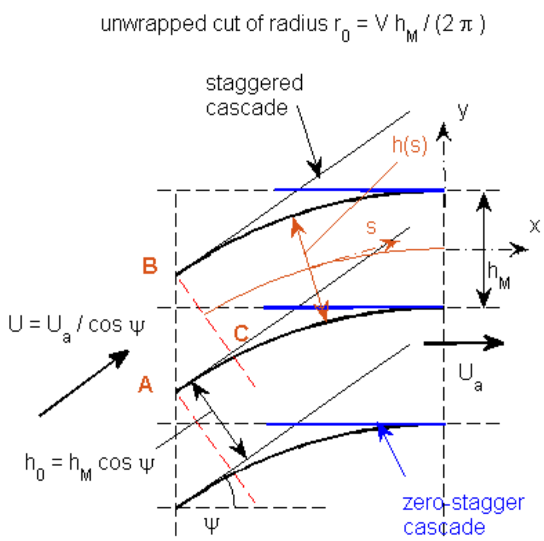
AIAA2016-2944; AIAA2017-3385 & 3702 papers

Future of fan noise prediction

Mode-Matching Technique in Bifurcated Waveguides (MMBW)



Needs:
- Fast-running prediction tools for sound generation and sound transmission mechanisms (unified theory)
- Eliminate strip theory (rectilinear discontinuities)
- Approach compatible with cascade/camber effect



Mode-matching technique:

- Field expansion in orthogonal modes in each sub-domain (annular spaces upstream and downstream of a blade/vane row, inter-blade/vane channels)

- Matching at interfaces to ensure continuity of the acoustic field: infinite system of equations

- Solving of the truncated system by matrix inversion: modal coefficients

Preliminary MMBW results

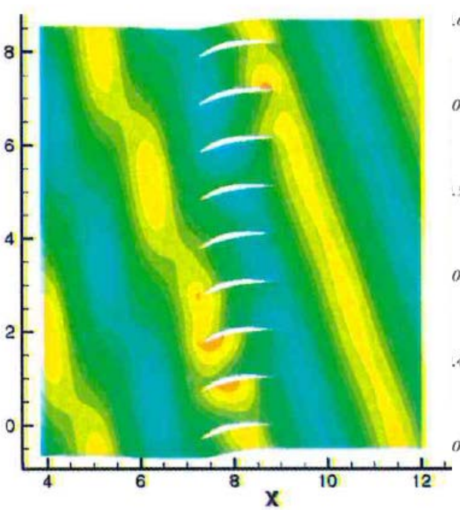
Impact of an acoustic wave

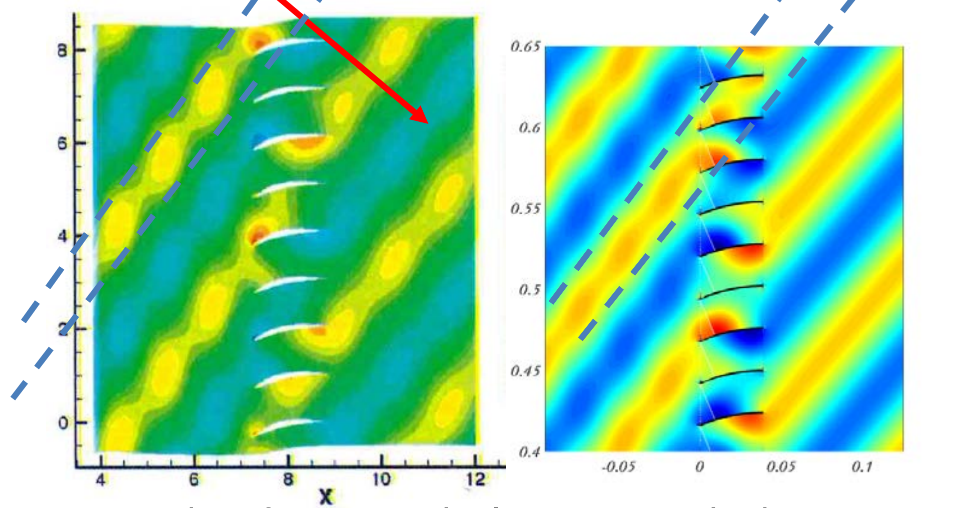
NASA SDT Test Case (cylindrical cut at 22.35 cm)

OGV: 54 stators; Mach number 0.4, 5726 Hz

Contamination by BC reflections

BASS Euler code | **MMBW (linear)** | **Code BASS Euler** | **MMBW (linear)**





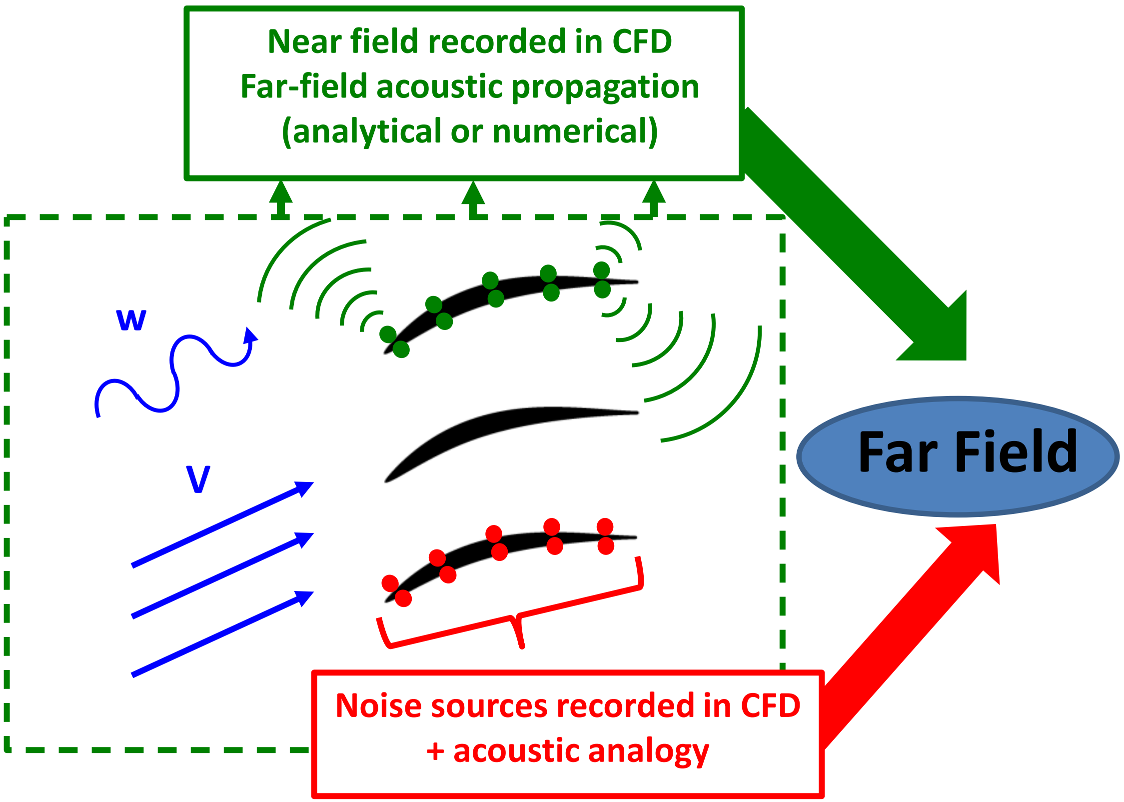
Upstream interferences; single cut-on mode downstream

mode 6 | **mode -12**

Excellent agreement with Hixon results without spurious reflections

R. Hixon, AIAA 2011-2706.

Numerical methods for fan noise prediction



Computational Aero-Acoustics (CAA):

DIRECT approach

\+ actual acoustic propagation

\- high-order schemes

HYBRID approach

\+ classical CFD solvers (even incompressible)

\+ complex source geometries

\- No feedback mechanisms

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Wang et al., ARFM 2006

Possible numerical methods for noise sources

Numerical simulation of acoustic sources on blades
(DNS is still too costly for a real case ($R_e>10^6$))

URANS (Navier-Stokes)

- Unsteady mean flow field with turbulence modeling
- Deterministic problems

→ **Tonal noise**

LBM/VLES

- Large-eddies resolved, small eddies are modelled
- Unsteady method limited to low Mach applications (M<0.5))
- Low dispersion for acoustic propagation

→ **Tonal/broadband noise**

LES (Navier-Stokes)

- Large-eddies resolved, small eddies are modelled
- Efficient method for high subsonic flows (precision)

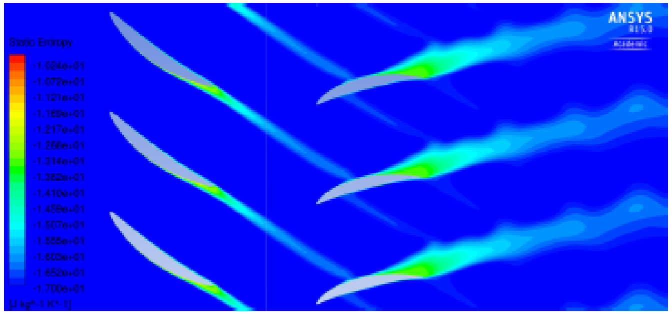
→ **Tonal/broadband noise**

Solvers used here

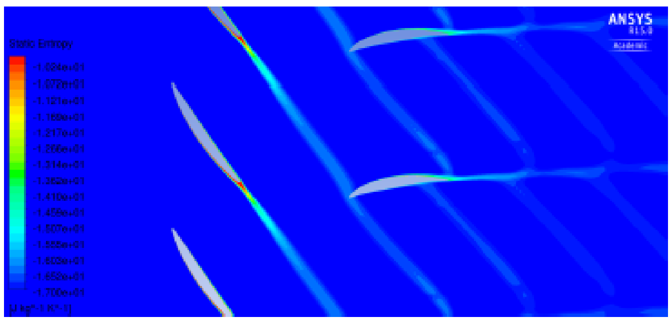
- **Navier-Stokes, CFX (ANSYS):** finite volume, 3D compressible flow, unstructured mesh, dedicated to turbomachines
- **LBM, Powerflow (Exa):** *low-Mach* 3D compressible flow, cubic mesh, turbomachine capabilities
- **Navier-Stokes, TurboAVBP** (Cerfacs-IFPen): finite element, 3D compressible flow, unstructured mesh, dedicated to turbomachines

Results of ANCF URANS simulations

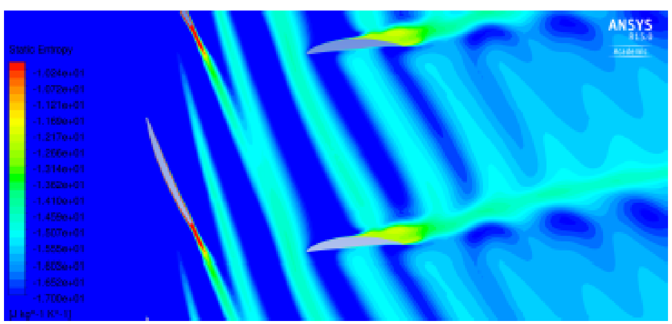
ETC 2015



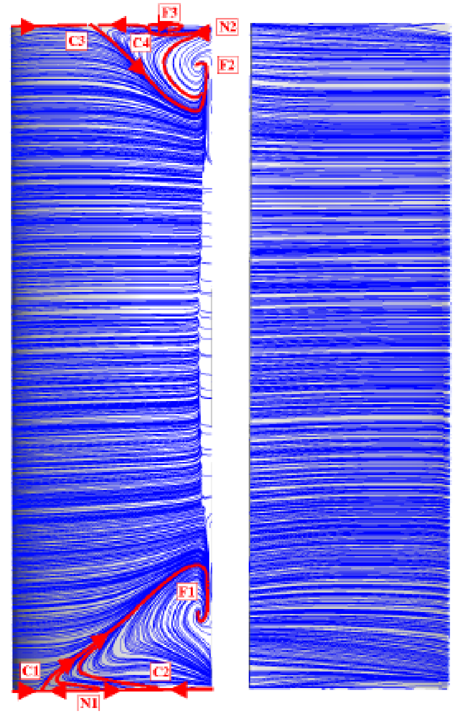
(b) U-RANS entropy flowfield at $h = 10\%$.

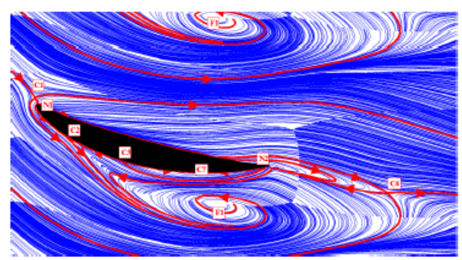


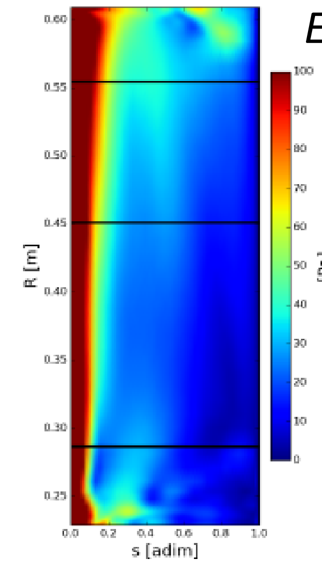
(d) U-RANS entropy flowfield at $h = 50\%$.



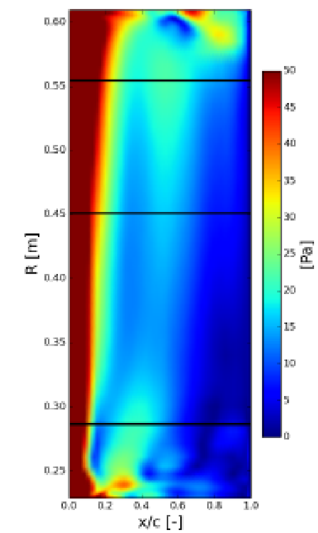
(f) U-RANS entropy flowfield at $h = 98\%$.







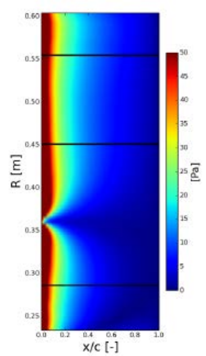
(a) RMS of the pressure jump fluctuations.



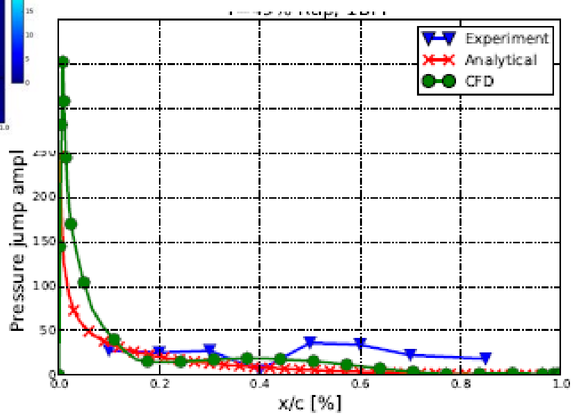
(b) Amplitude of the CFD pressure jump, $f = BPF$

Hub and tip corner separations on stator

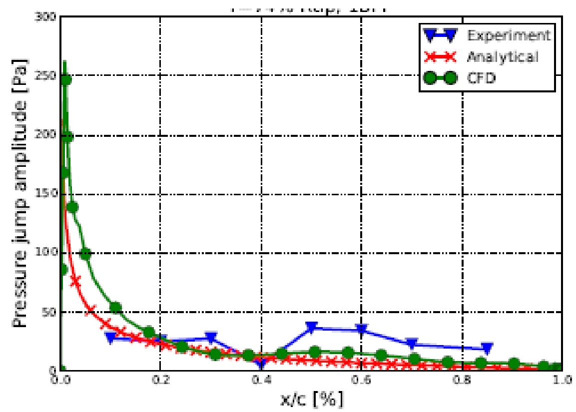
Comparison of pressure jumps



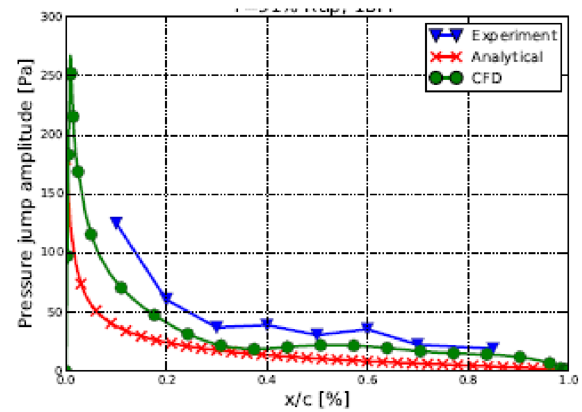
1BFP



(a) $0.49\,R_T$

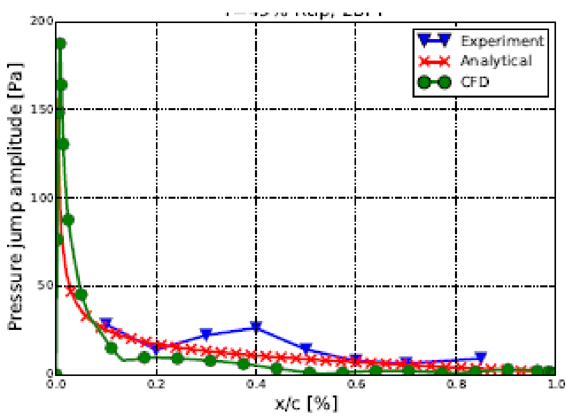


(b) $0.74\,R_T$

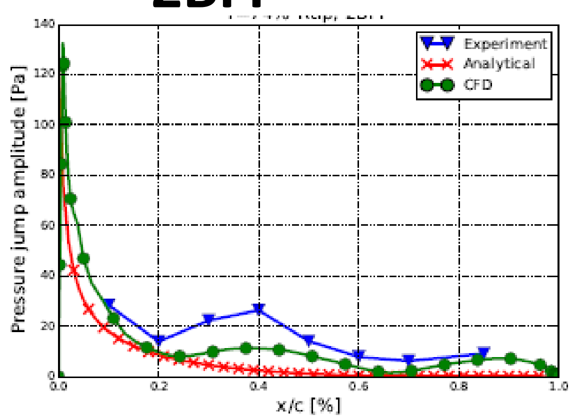


(c) $0.91\,R_T$

2BFP



(a) $0.49\,R_T$



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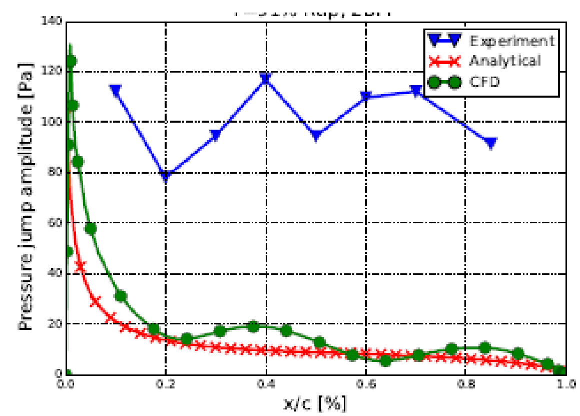


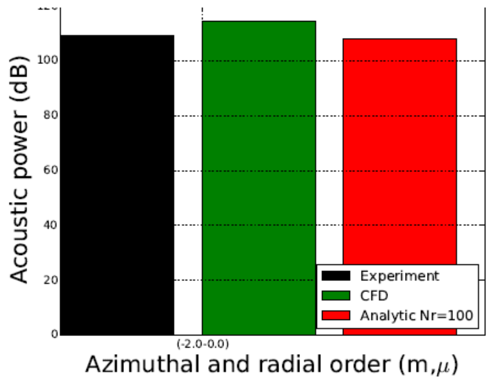
(c) $0.91\,R_T$

Good CFD/analytical agreement
Differences seen in the corner separations

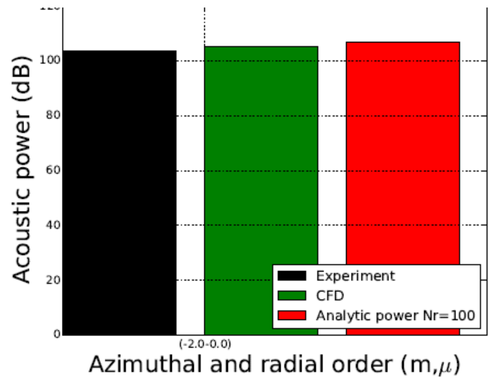
ETC 2015, AIAA2014

Comparison of acoustic powers

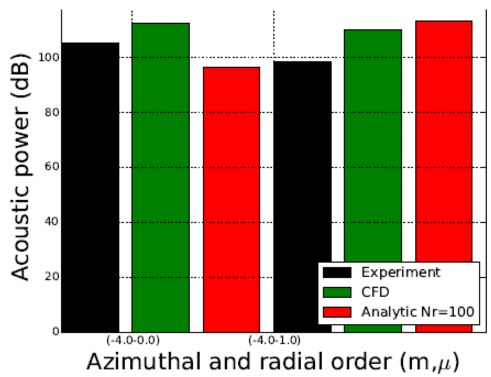
Frequency	Upstream power			Downstream power		
	EXP	Ana	CFD	EXP	Ana	CFD
$1 \times BPF$	109.4	108.08	113.73	104.9	106.99	103.95
$2 \times BPF$	106.3	113.32	114.75	110.9	112.21	108.63
$3 \times BPF$	102.9	97.22	108.32	112.9	106.97	110.03



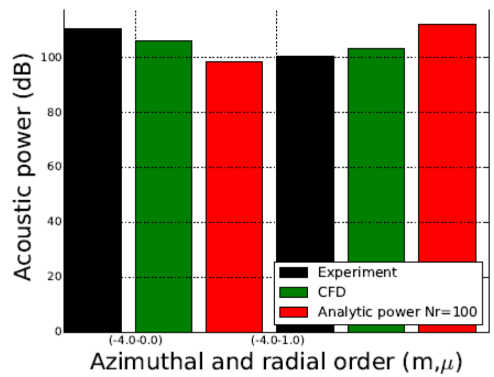
(a) Upstream power, $1 \times BPF$



(b) Downstream power, $1 \times BPF$



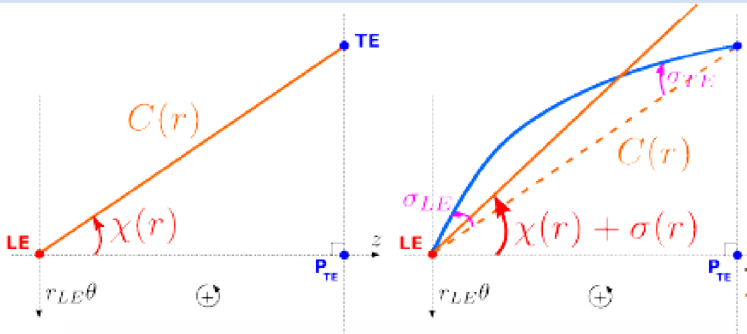
(c) Upstream power, $2 \times BPF$

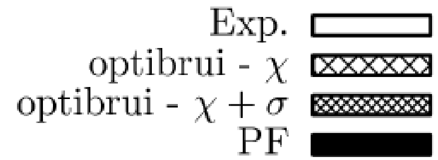


(d) Downstream power, $2 \times BPF$

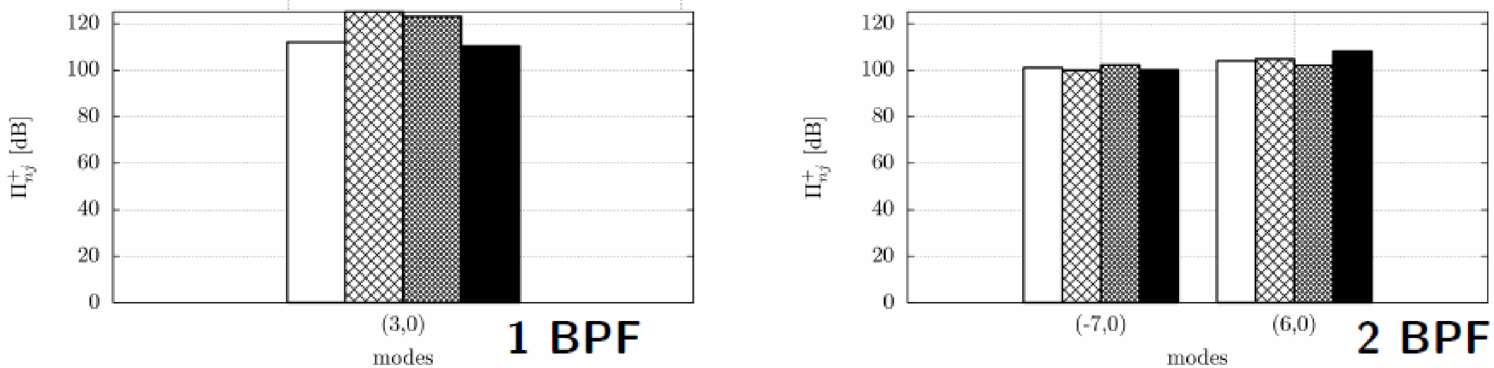
Good CFD/analytical/experimental agreement

Comparison of LBM acoustic powers

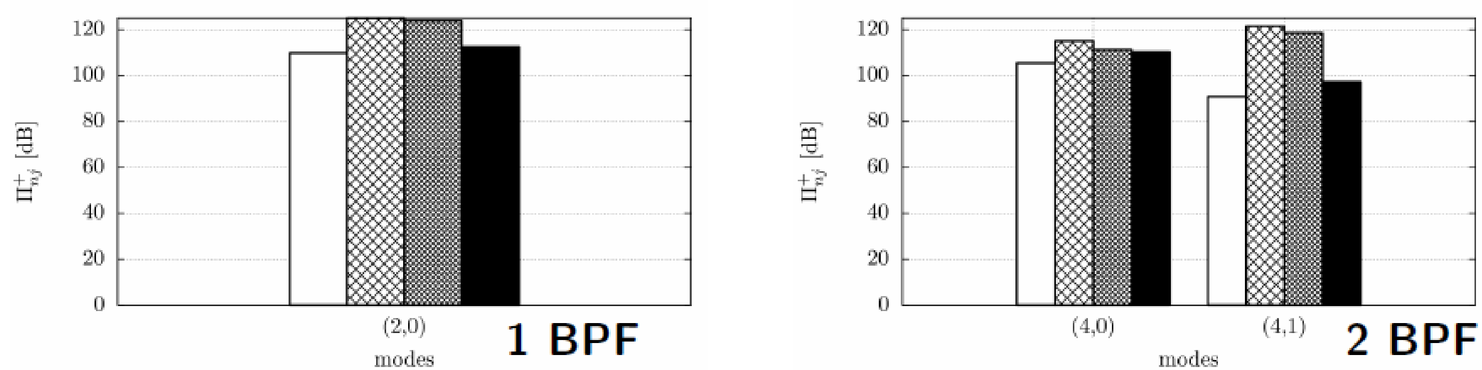




13-HC



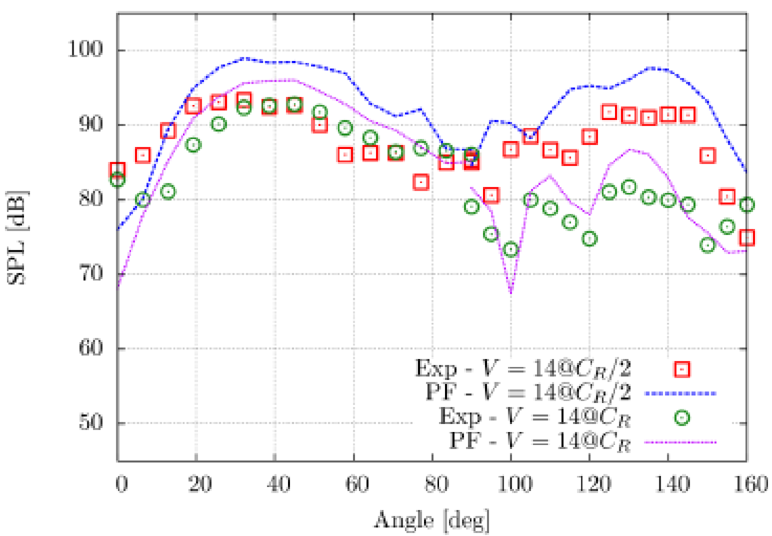
14-HC

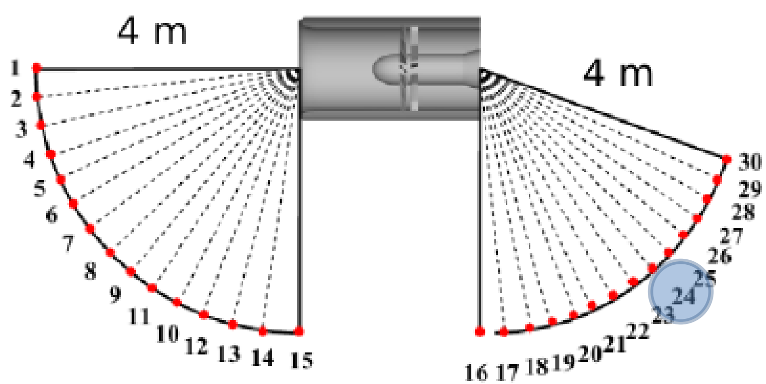


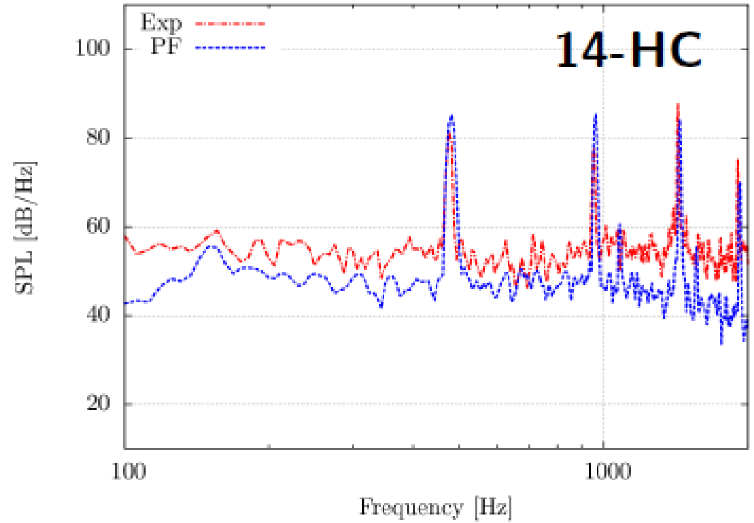
Good CFD/analytical/experimental agreement
Moderate influence of LE camber

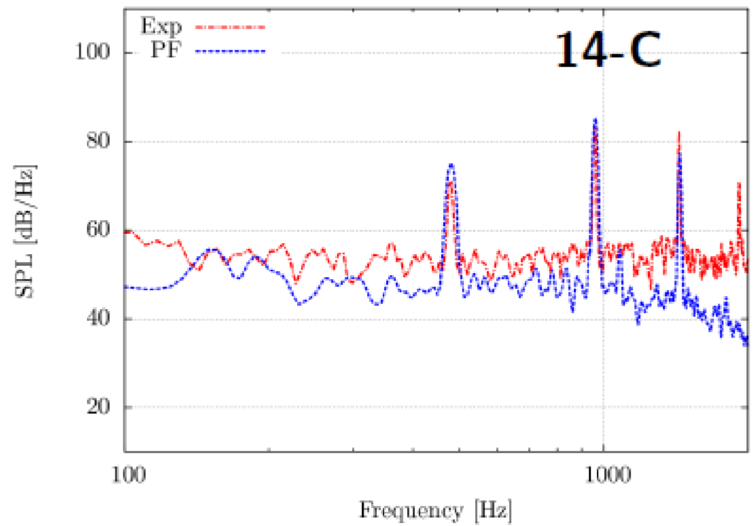
LBM *Direct* far-field acoustics

1 BPF





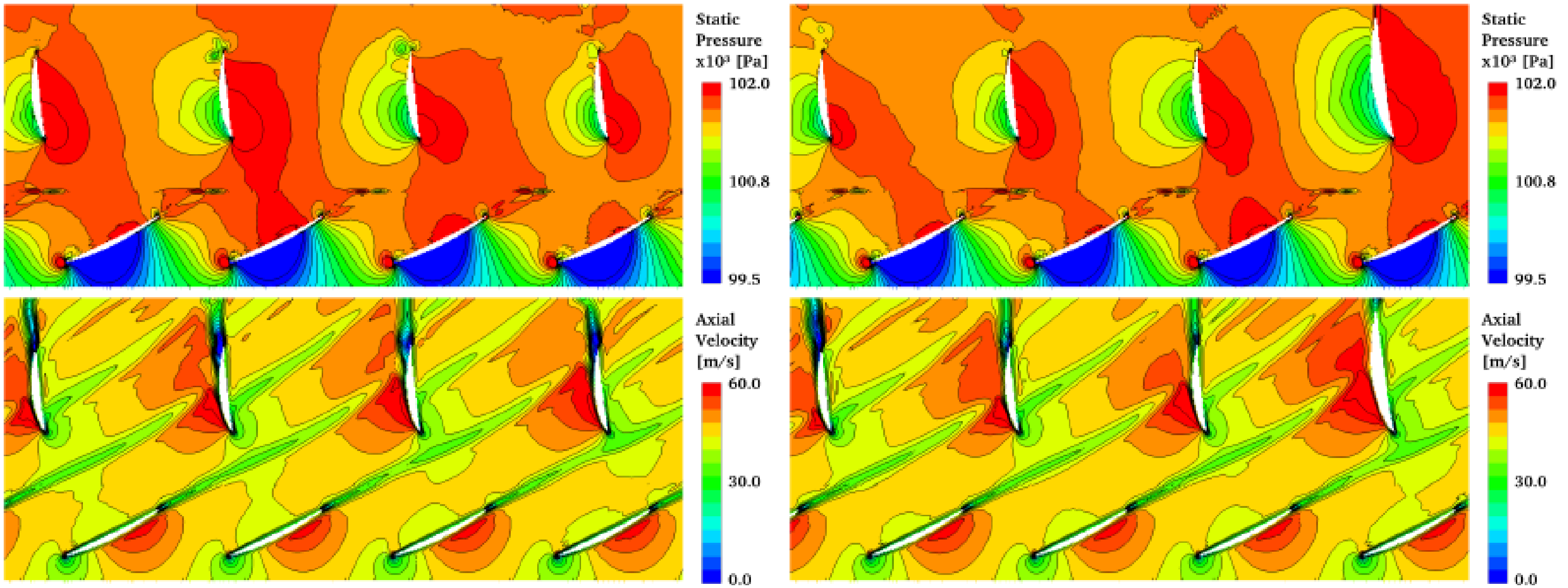




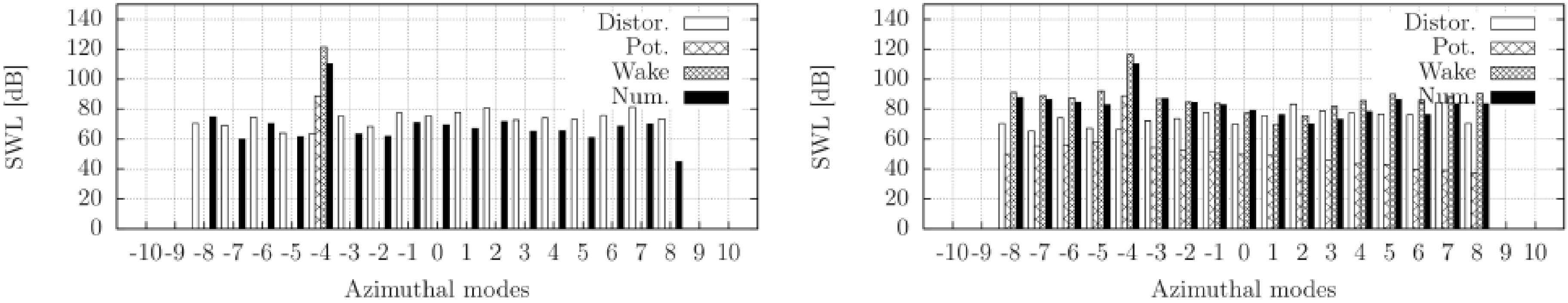
Good CFD/analytical/experimental agreement

NCEJ 2015

Effect of heterogeneous stators



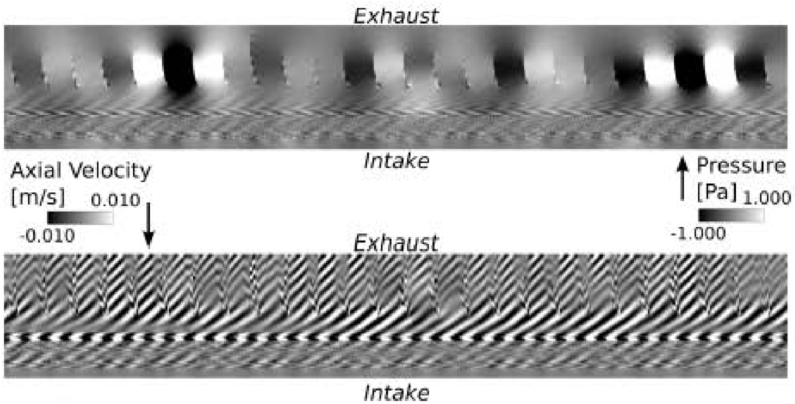
(a) Homogeneous - $V = 14$ (b) Heterogeneous - $V = 14$



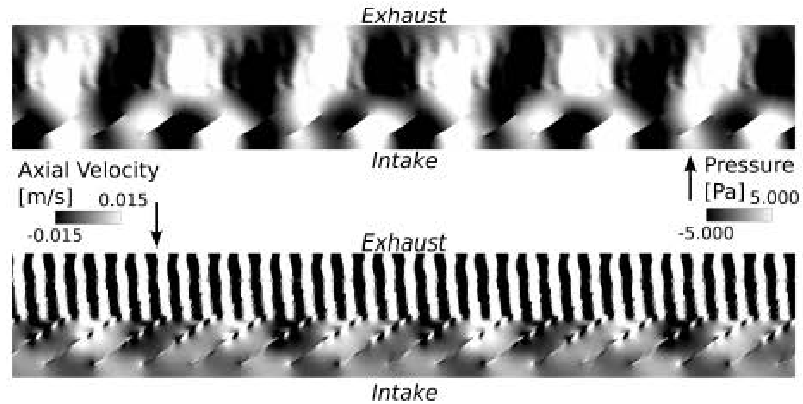
Good CFD/analytical/experimental agreement
Wake interaction and inlet distortion dominant noise

AIAA J 2017

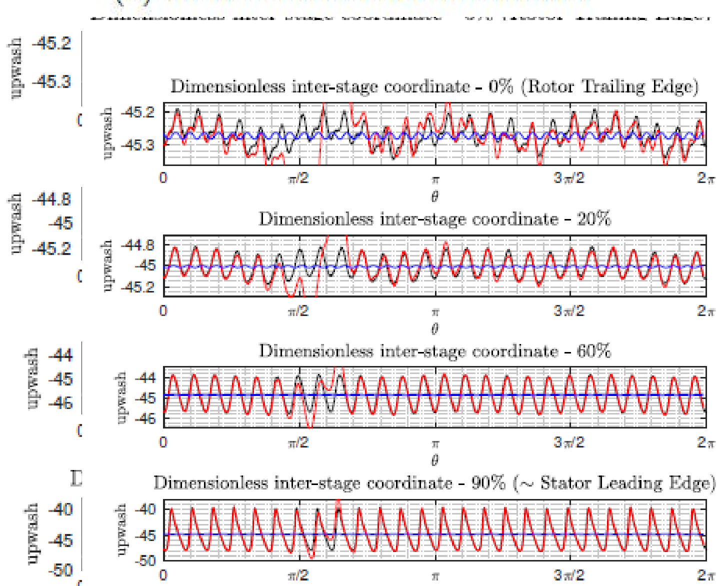
Evidence of Parker's resonance

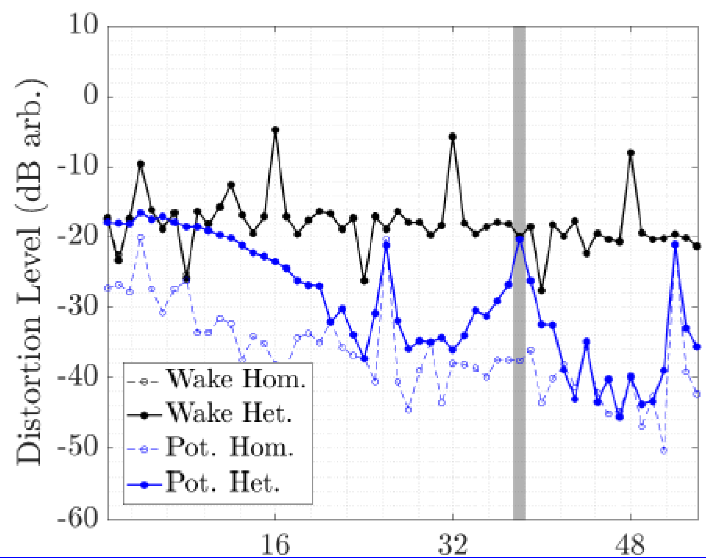


(a) In the stator reference frame.



(b) In the rotor reference frame.



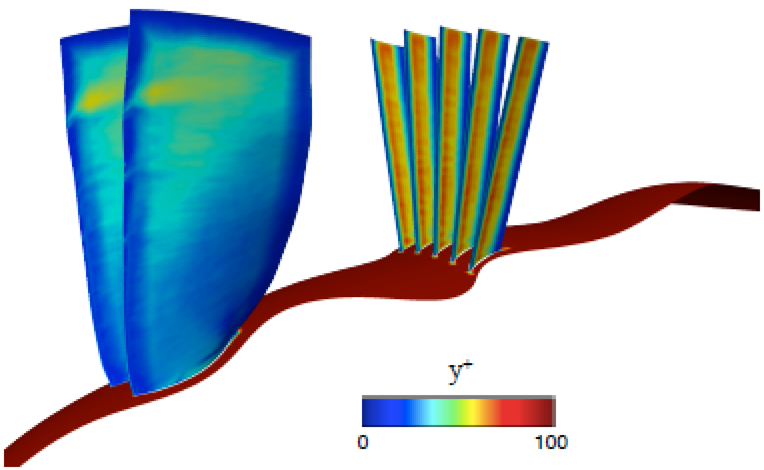


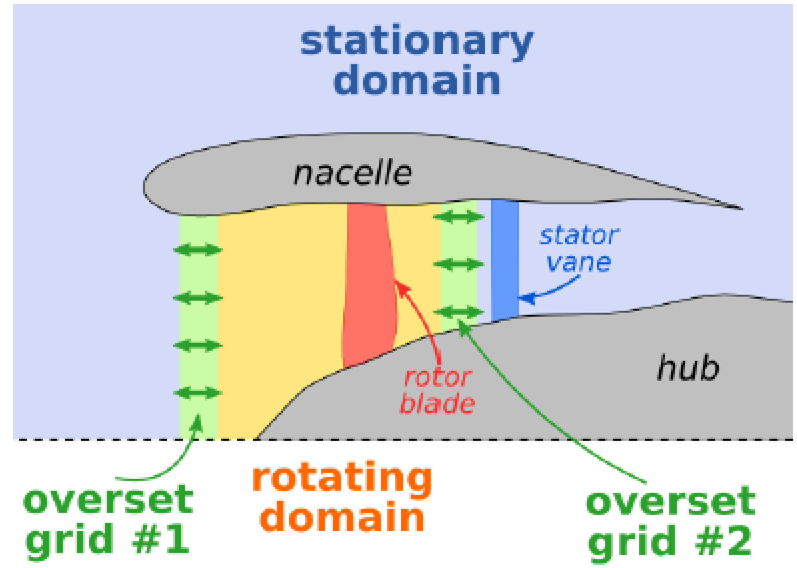
Non-linear interaction between stator potential field and rotor wakes
Parker's β mode seen in stator (quasi-stationary)

AIAA J 2017

Test-cases AIAA-RC1 (SDT fan) -1

54 stators (reference); approach condition





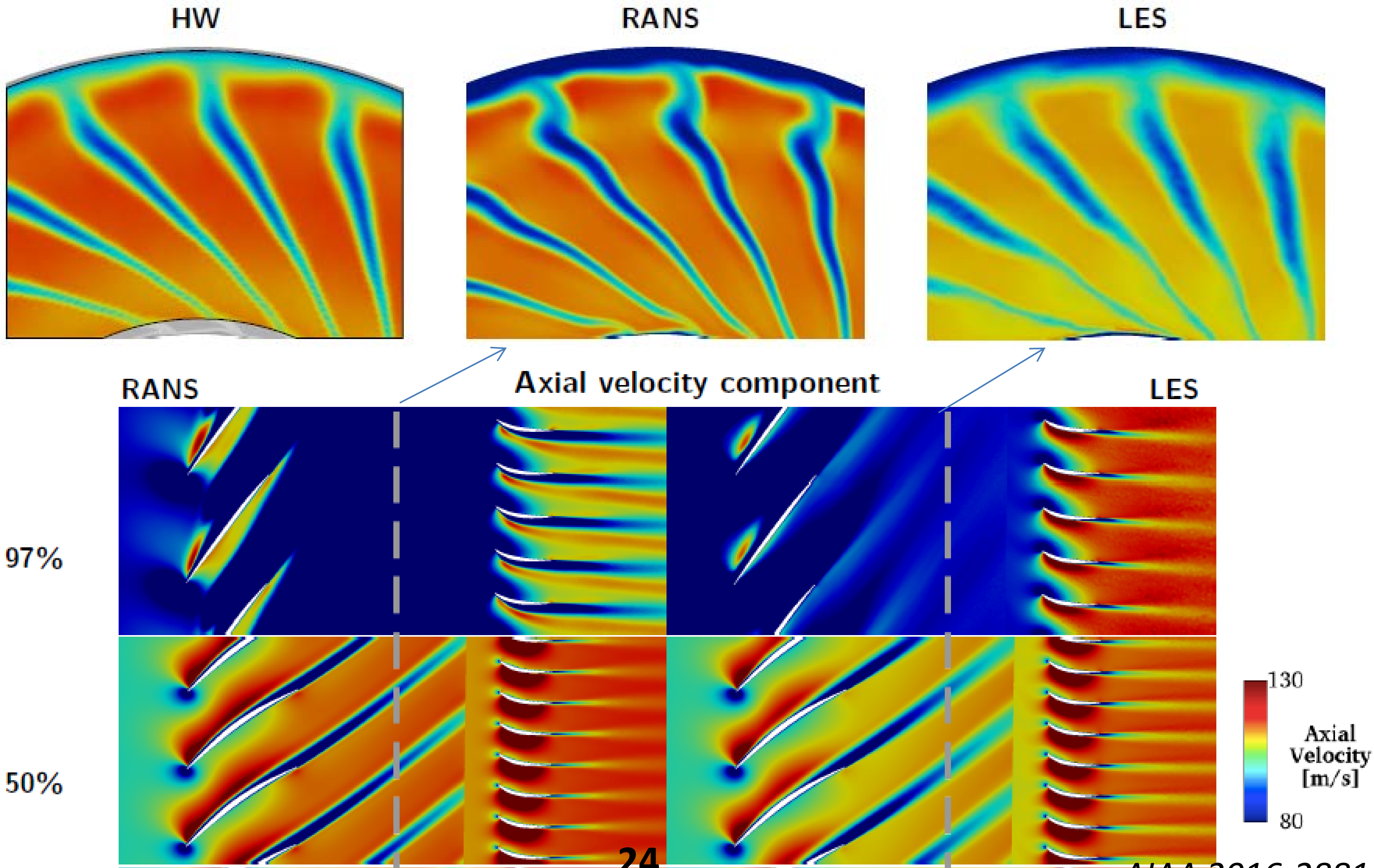
	Massflow rate		Total pressure ratio	
Experiments*	26.54 kg/s		1.154	
RANS	26.14 kg/s	-1.5%	1.160	+0.5%
LES	25.78 kg/s	-2.8%	1.162	+0.7%

Rescaled geometry to reduce blade count
Good overall performance prediction (similar as LBM)

AIAA 2016-2881

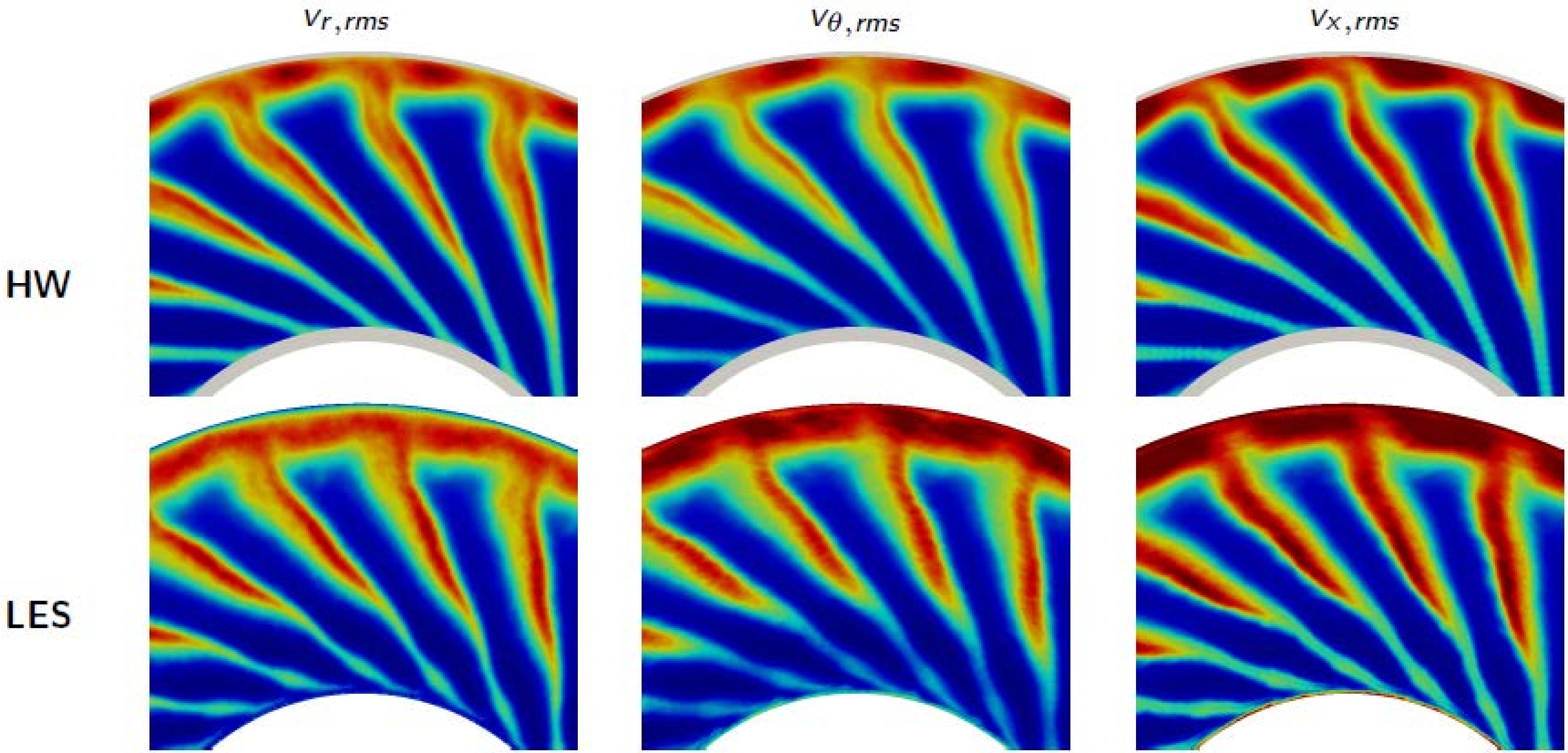
Test-Case AIAA-RC1 (SDT fan) -2

Mean streamwise Mach number at mid rotor-stator distance



AIAA 2016-2881

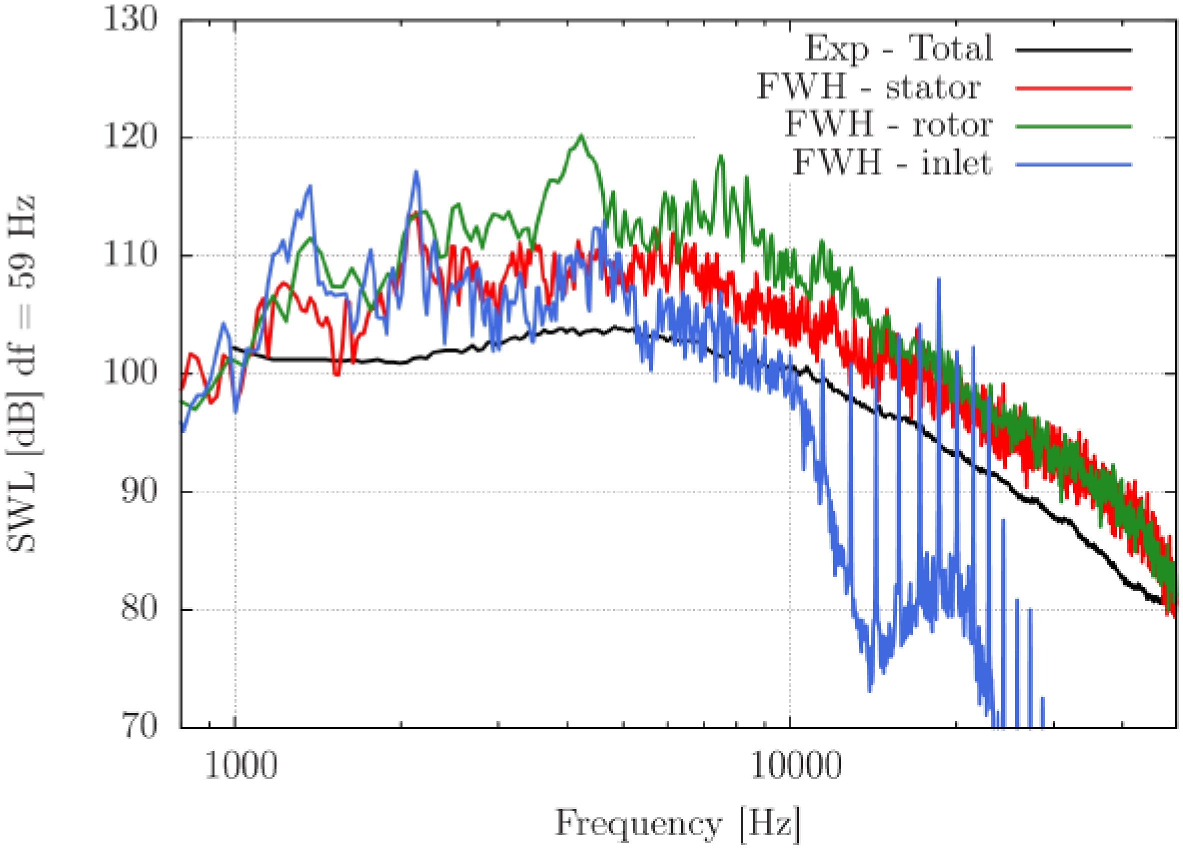
Test-Case AIAA-RC1 (SDT fan) -3



Excellent turbulence predictions (all rms levels)
Quasi local wake turbulence isotropy

AIAA 2016-2881

Test-Case AIAA-RC1 (SDT fan) -4

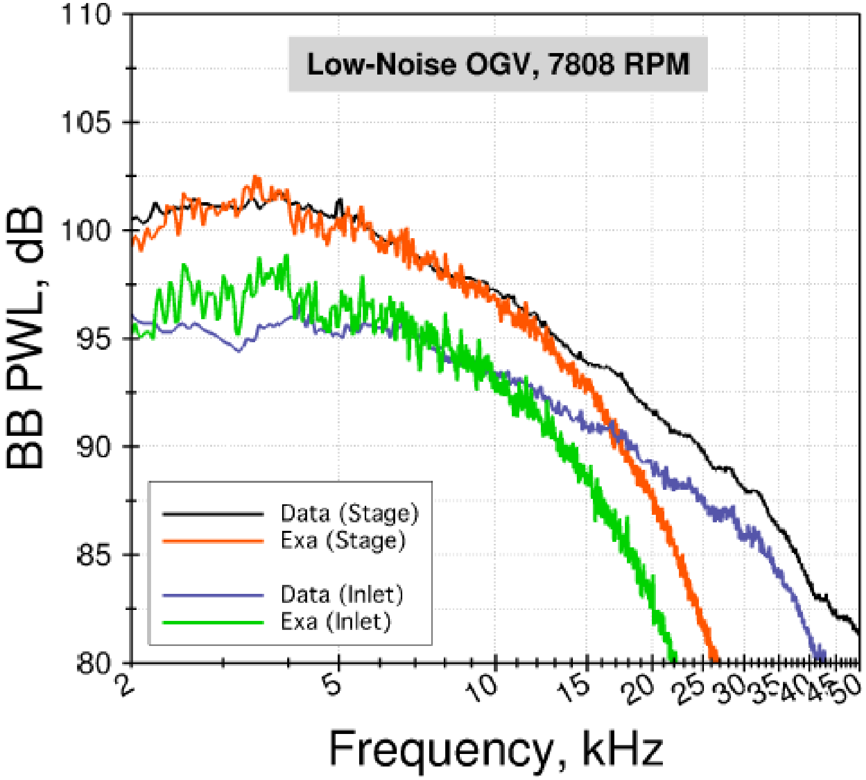


Good overall shape prediction (including inlet porous surface)
Overprediction of rotor contribution (tip separation and vortices)
On-going Goldstein analogy prediction
Future: high Mach number cases

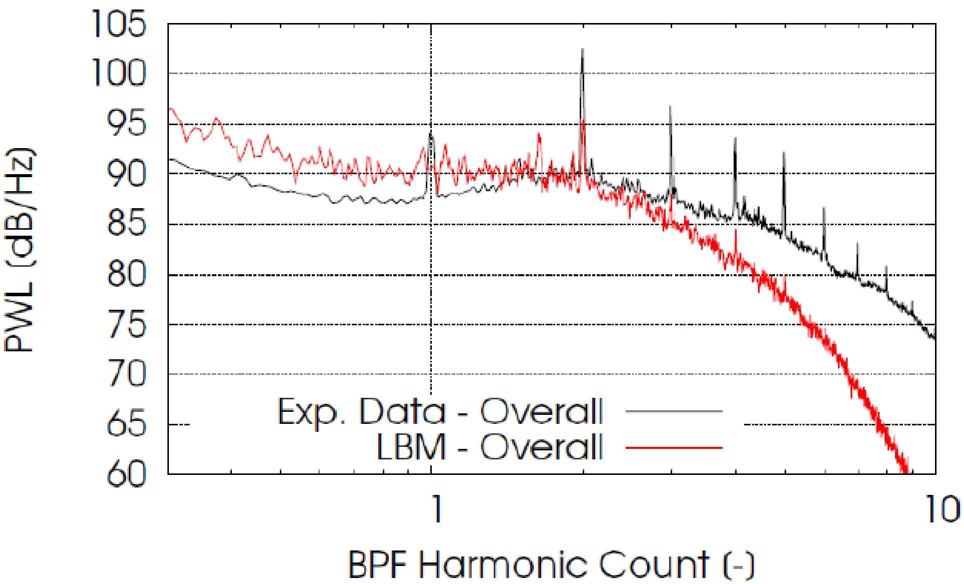
AIAA 2016-2881

Future: High Mach number LBM

Approach



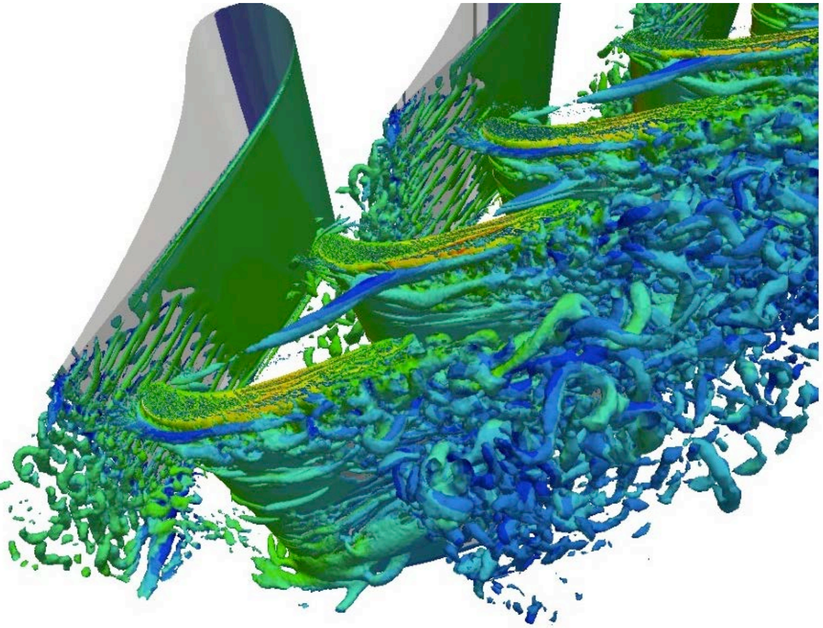
Cutback



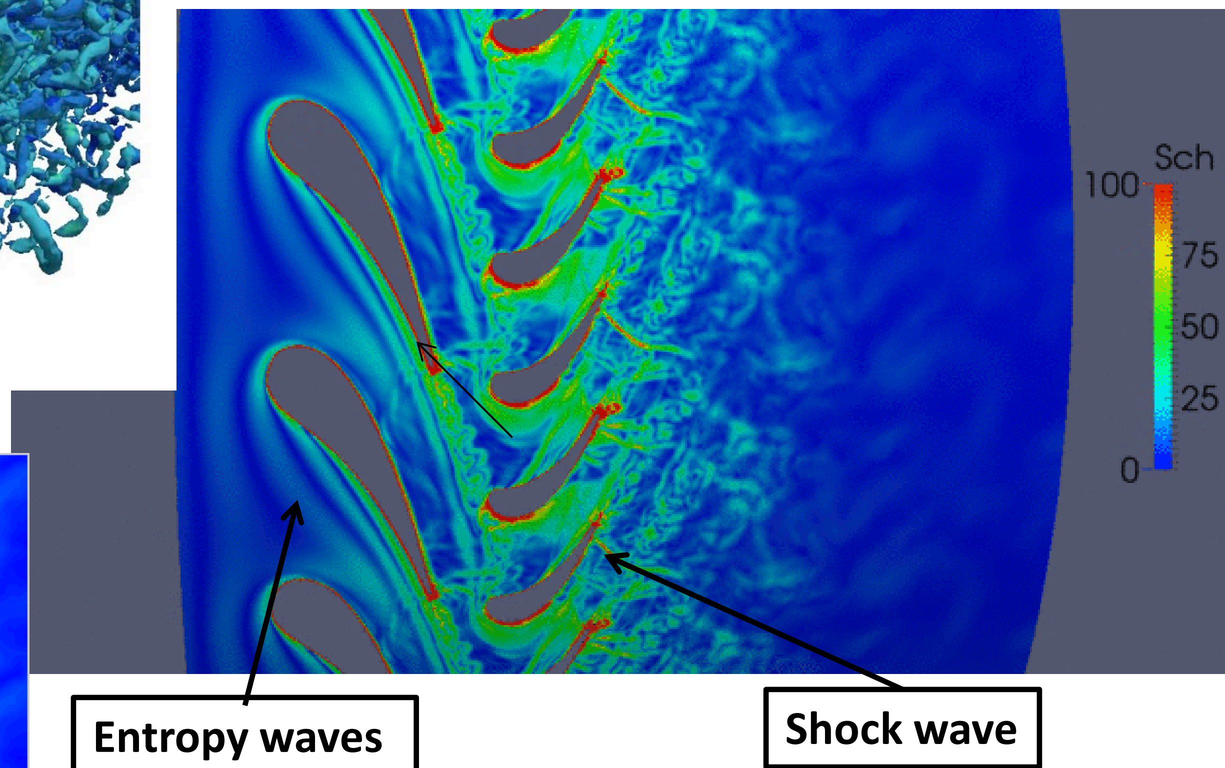
Excellent agreement for all approach configurations
Good preliminary high-speed predictions (with shocks)

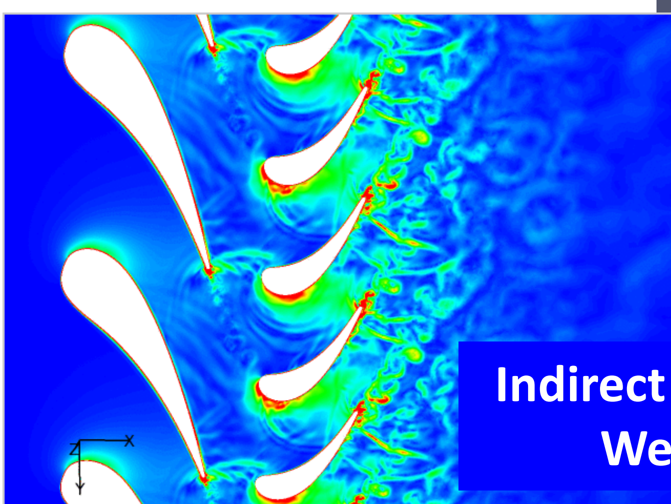
AIAA 2017 benchmark

Acoustic analysis of HP turbine noise



LES of MT1 transonic turbine with generation/transmission of entropy and acoustic waves





Indirect combustion noise produced in first HP turbine row
Weak reflection toward the combustion chamber

IJA 2016

Conclusions

- Analytical models of tonal and broadband noise developed from Goldstein's analogy and finite-chord flat plate responses (Schwarzchild or Wiener-Hopf methods or mode marching) are efficient and accurate pre-design tools for fans, propellers and compressors.

- Satisfactory extension to swirl and lined walls of Wiener-Hopf models; Mode matching in bifurcated waveguides promising method.

- These models are developed in free field and in duct with solidity effect or not, for most noise mechanisms.

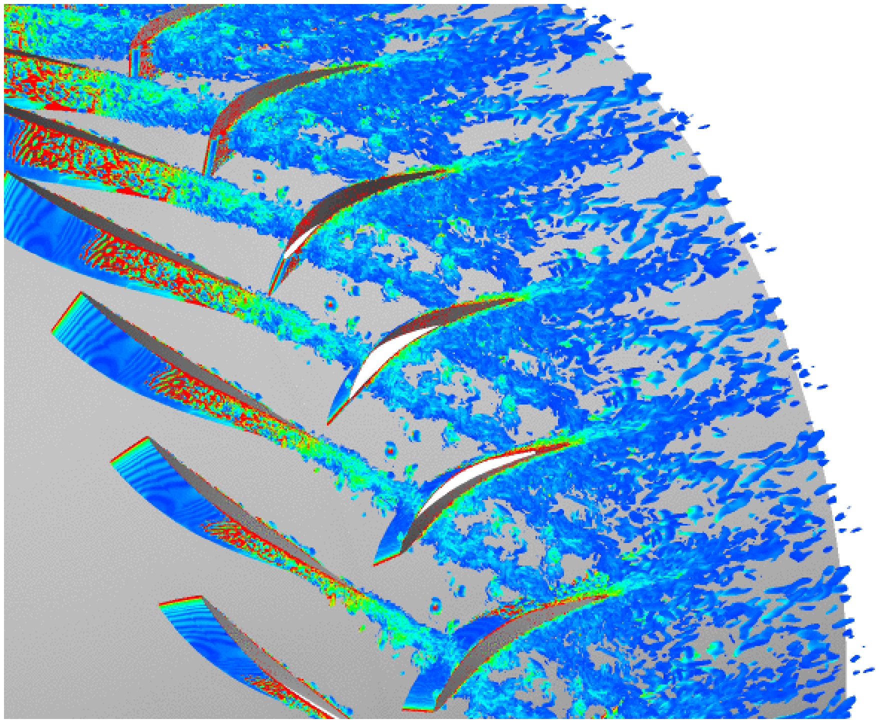
- URANS simulations efficient and accurate methods to obtain tonal noise sources

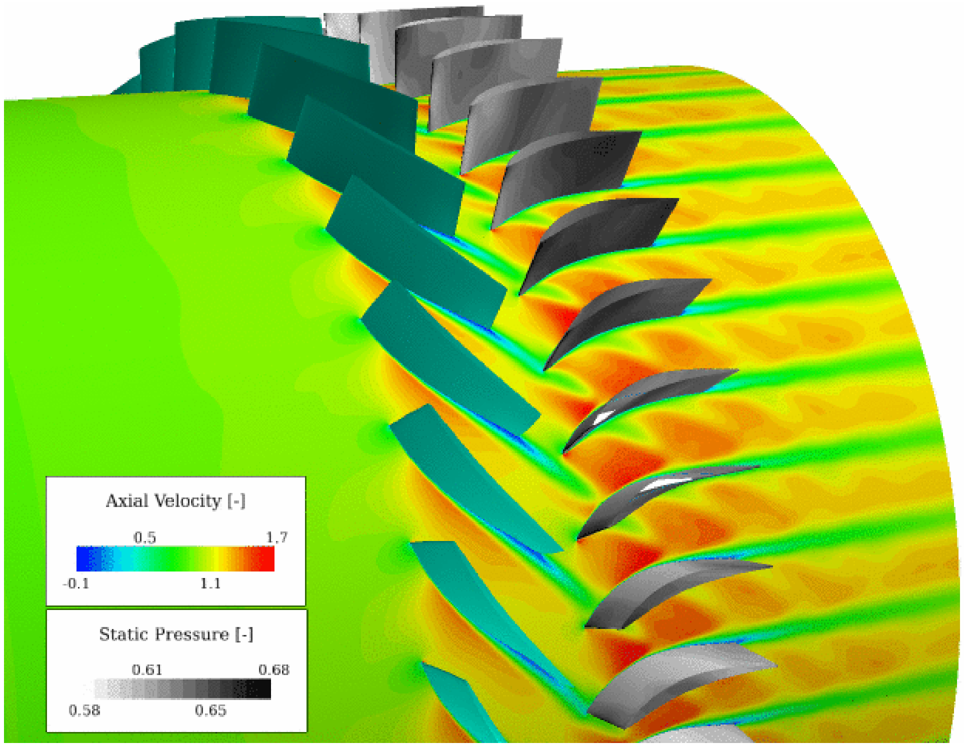
- The direct simulation of broadband noise (LES) for turbofans remains a challenge, but first results are promising!

- LBM is able to reproduce both tonal and broadband noise of most interaction mechanisms even at high Mach number

Validation and analysis by simulations

Snecma CME2 Compressor / Turb'flow Simulations





LES: Broadband noise

AIAA 2013-2042

URANS: Tonal noise

AIAA j 2014 (x2); JPP 2014

Thanks for your attention