Fan Tonal and Broadband Noise Simulations at Transonic Operating Conditions Using Lattice-Boltzmann Methods

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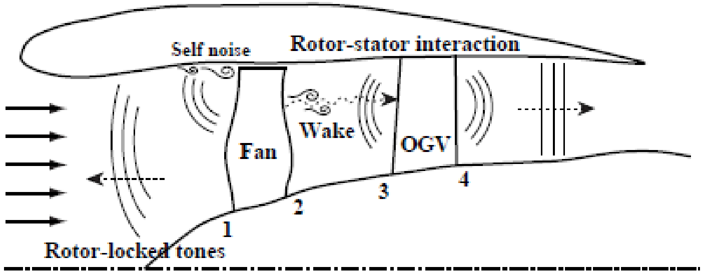
TU-Delft/3DS Workshop on PowerFLOW simulations of aircraft noise

Motivation



- Noise radiated by modern fan stages are becoming comparable to jet noise due to engine trends:
  - ▷ Increase in bypass ratio
  - ▷ Transonic tip speeds
  - ▷ More compact, thus reduced fan-OGV distance
- 3 main fan stage noise sources:
  - ▷ Rotor-stator interaction noise
  - ▷ Rotor self noise: ingested boundary layer
  - ▷ Rotor-locked tones (for transonic tip speed)

- Objective: demonstrate of the capability of SIMULIA PowerFLOW to simulate broadband and tonal fan noise for a wide variety of operating conditions and geometry variations

Outline

GE/NASA Fan Stage SDT

Computational Approach

Stage Performance and Flows

Farfield Noise

Modeling Multiple Pure Tones

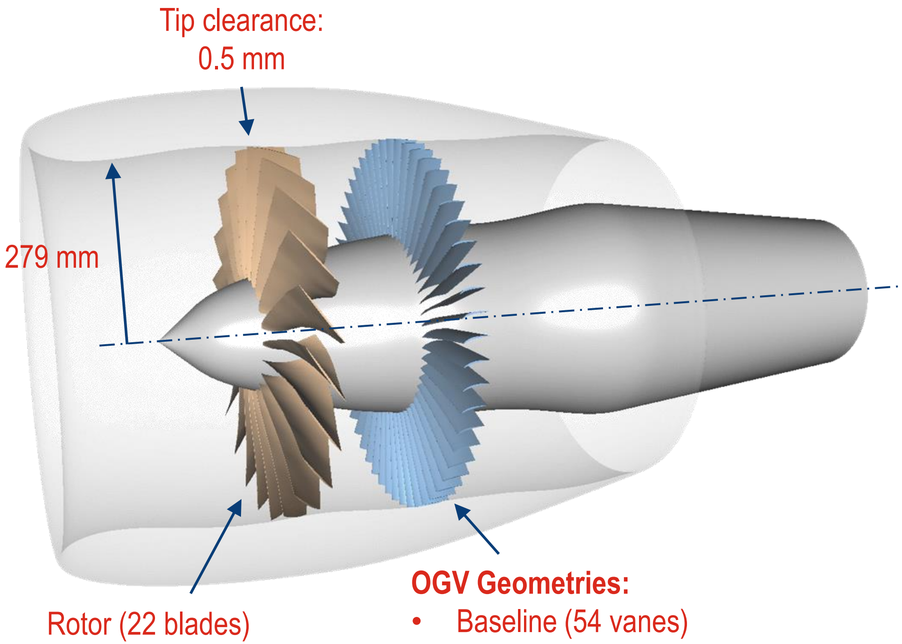
Summary

SDT Fan/OGV Stage

- GE/NASA fan stage model: ø 22 in
- Wind-tunnel tests at different RPM:

Operating Conditions	% Design Fan Speed	Fan Tip Speed (m/s)	Fan RPM
Approach	61.7 %	228.1	7809
Cutback	87.5 %	323.6	11075
Sideline	100 %	369.8	12657

- 3 OGV configurations designed:
  - Baseline: 54 straight vanes
  - Low-Count: 26 straight vanes
  - Low-Noise: 26 swept vanes



OGV Geometries:
- Baseline (54 vanes)
- Low-Count (26 vanes)
- Low-Noise (26 swept vanes)

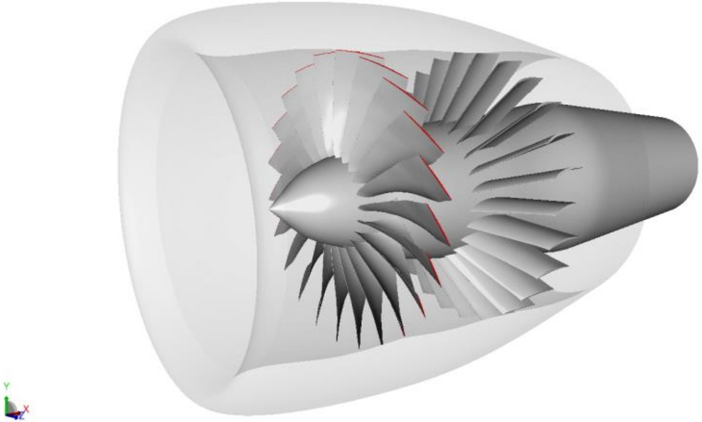
Woodward, “Comparison of Far-Field Noise for Three Significantly Different Model Turbofans”, AIAA 2008
Envia et al., “An Assessment of Current Fan Noise Prediction Capability”, AIAA 2008

Computational Approach

- Simulia PowerFLOW solver:
  - ▷ Lattice-Boltzmann method for subsonic & supersonic flows
  - ▷ LBM-VLES turbulence model
  - ▷ Extended turbulent wall model to account for pressure gradients at high Re#
- Cartesian grid with several resolution regions:
  - ▷ Finest cell size at fan tip gap (0.5mm): previous resolution studies showed small impact on farfield noise
  - ▷ Leading and trailing edges of fan blades and OGV: 0.183mm
    - This region covers full rotor blades in "Refined rotor" grid
  - ▷ Blades and OGV offsets at 0.366mm
  - ▷ Bypass channel and intake BLs at 0.732mm
  - ▷ Permeable surface for FW-H at 1.46mm

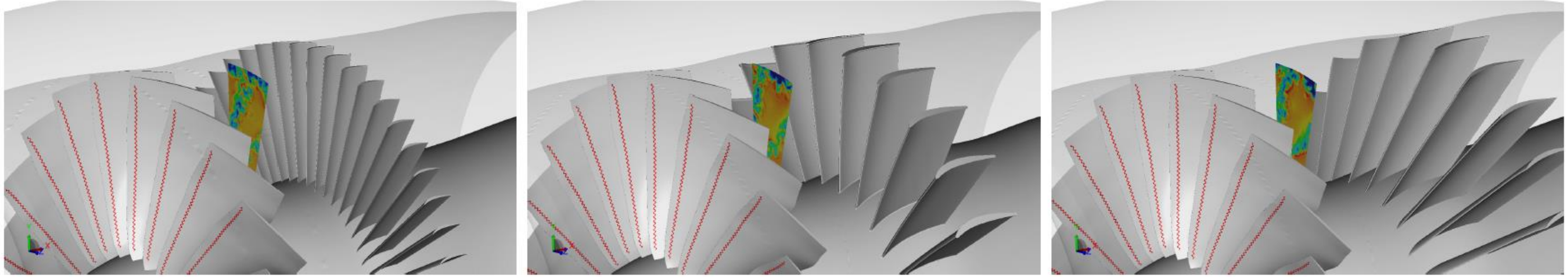
Simulation Statistics

Grid Resolution	Fan Tip Cell Size (mm)	# Cells	Turn-Around Time (1000 cores)
Coarse	0.122	430 M	1 day
Fine	0.0915	885 M	2.5 days
Refined Rotor (x2 near-wall)	0.0915	953 M	5 days

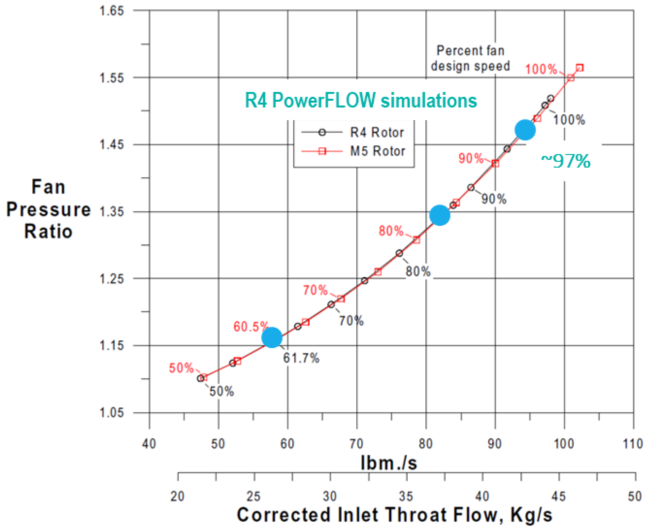


OGV Configurations

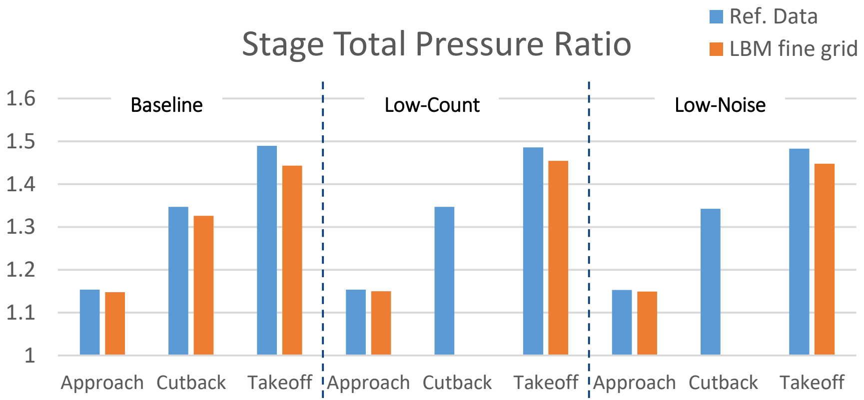
- Sideline/Take-Off Operating Point: 12657 rpm (100%)
- Three different OGV configurations were tested:
  - Baseline: 54 vanes
  - Low-Count: 26 vanes
  - Low-Noise: 26 swept vanes

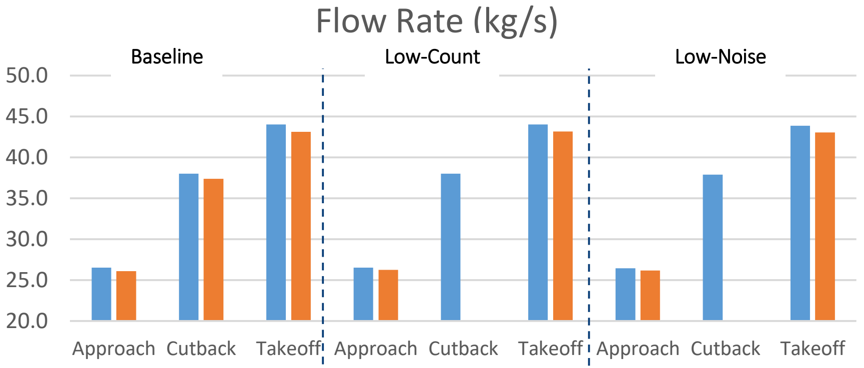


OGV Configuration – Engine Performance

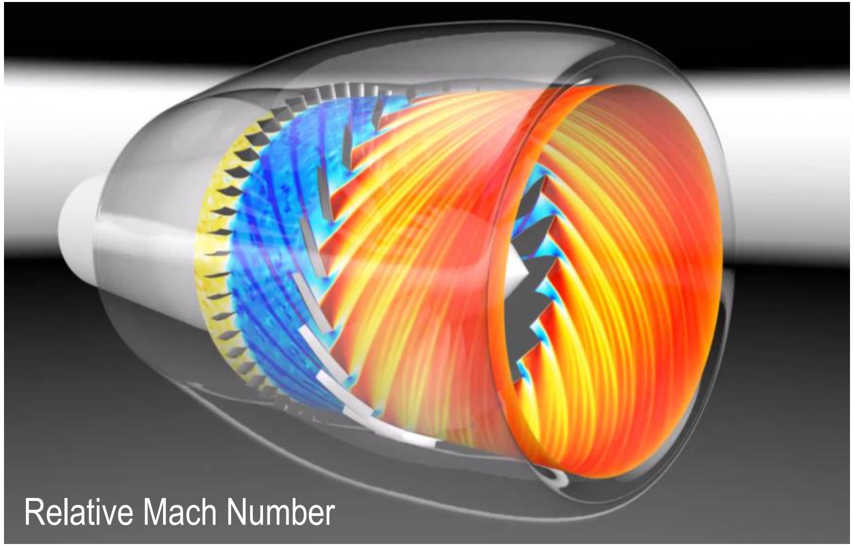


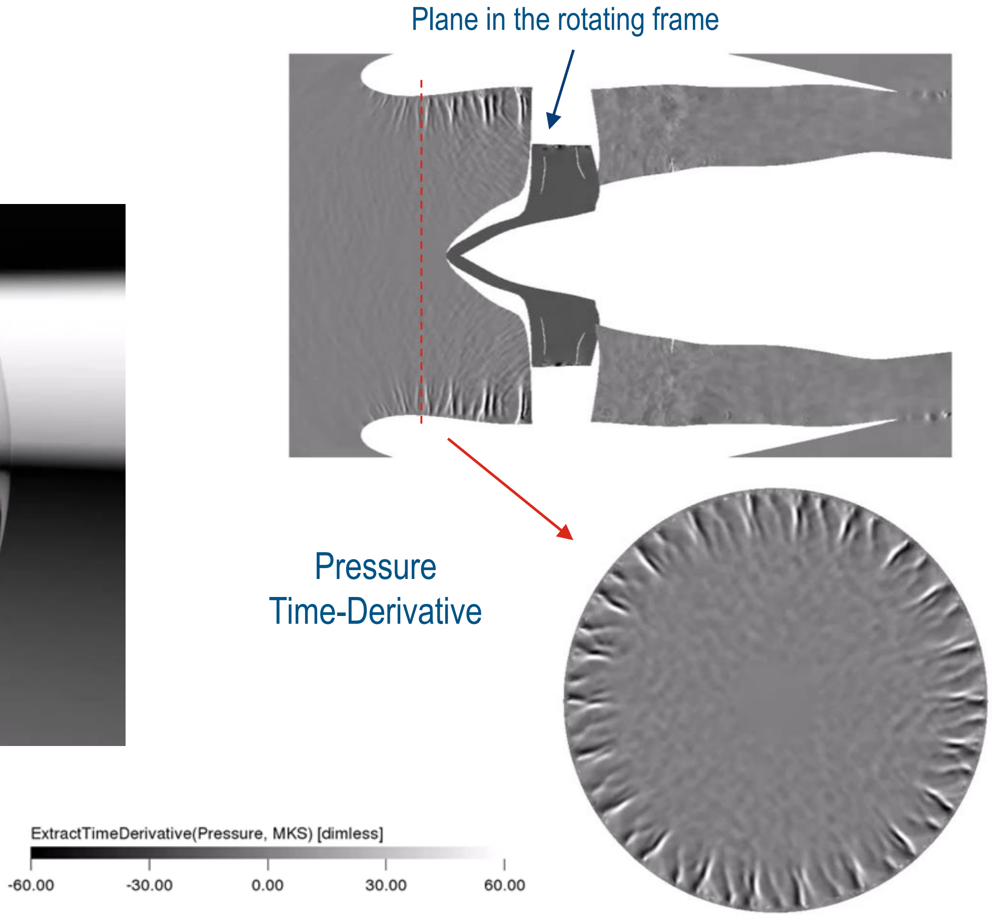
- ▷ Very good agreement with experiments in the pressure – mass flow curve
  - ▸ Highest simulated point slightly under 100% RPM
  - ▸ Slight mass flow & total pressure underprediction at iso-RPM (2-3% max).
- ▷ Almost no difference between OGV configurations





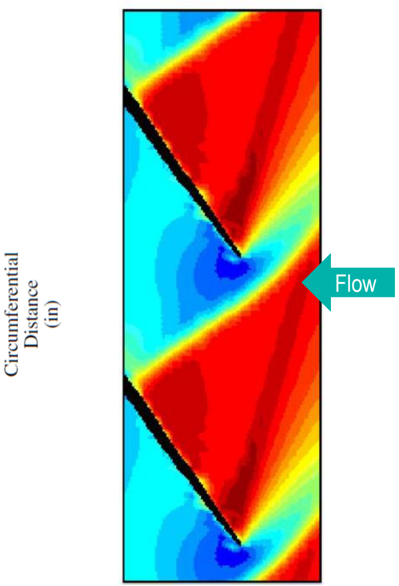
Instantaneous Flows


Relative Mach Number



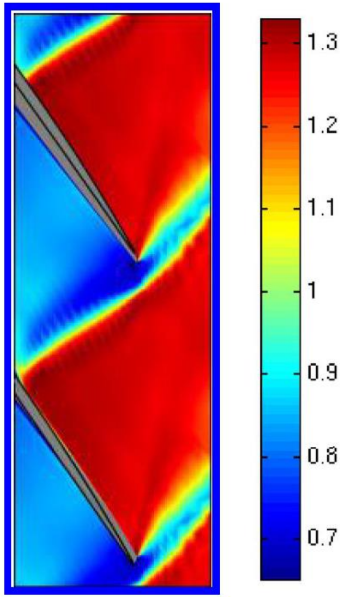
Shock Waves at Sideline Conditions

Experimental Data

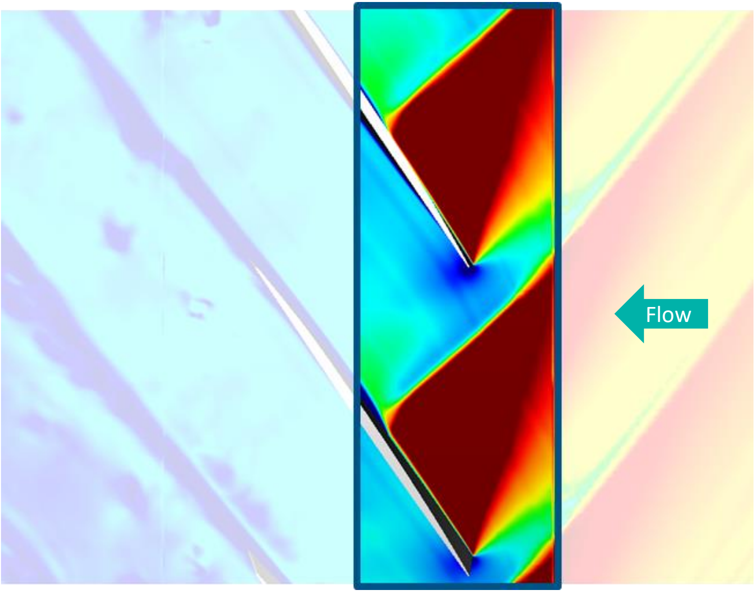


DES**

r/R = 95%



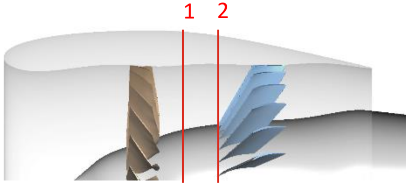
LBM Simulation



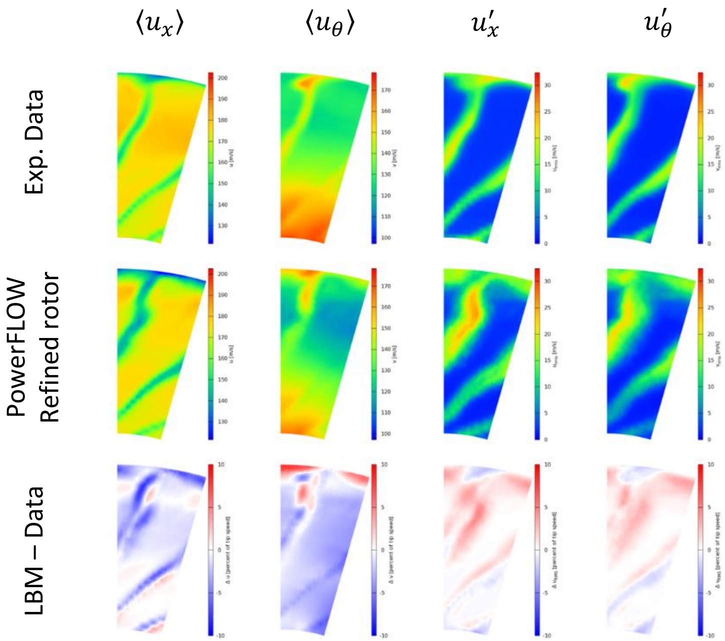
**Shur et al., “Unsteady Simulations of a Fan/Outlet-Guide-Vane System. Part 1: Aerodynamics and Turbulence” AIAA 2017-3875

Shock waves slightly earlier than in experiments
Possible thicker boundary layers inducing higher blockage

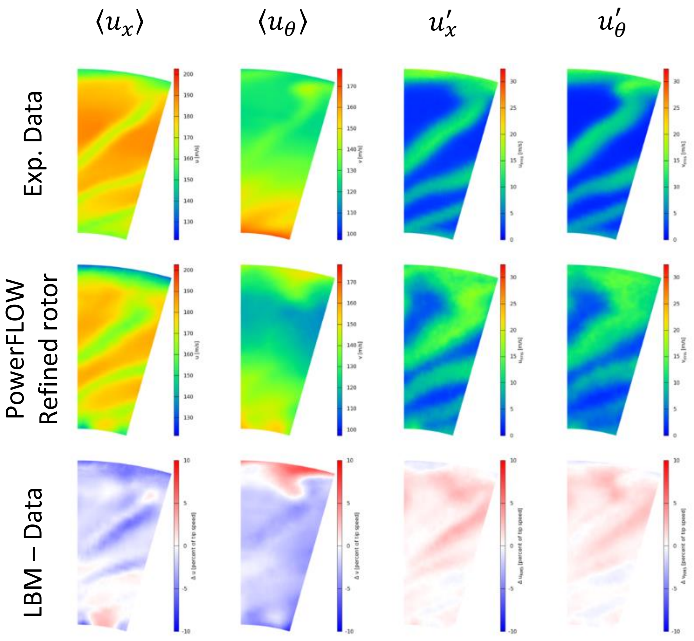
Interstage Flows



▶ LDV Station #1



▶ LDV Station #2



+10%

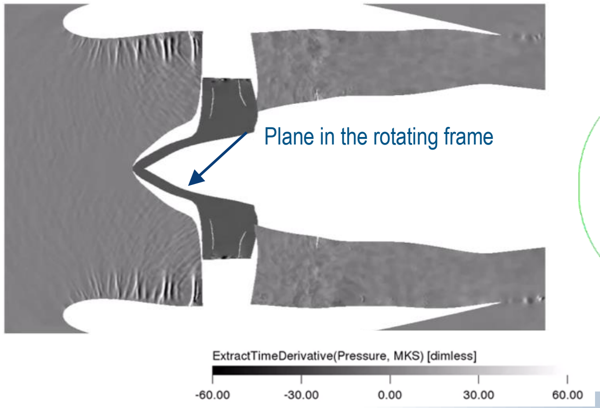
-10%

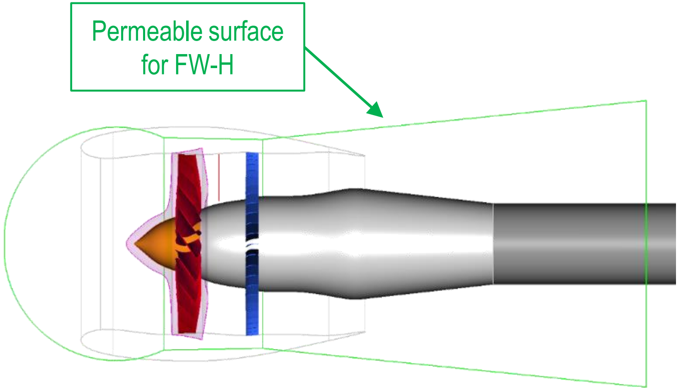
- Better wake deficit prediction / equivalent width
- Increase in velocity RMS levels: closer to LDV data

Farfield Noise Computations

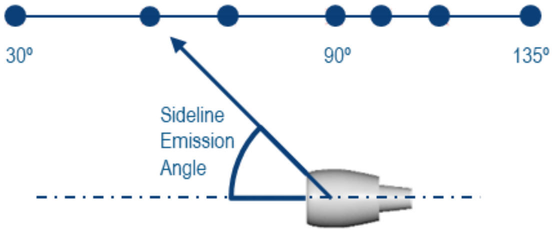
- Unsteady flows are recorded on a permeable surface around the engine
- FW-H integral method is used to compute far-field noise on a sideline array of microphones:
  - ▷ Pressure time series from microphones along a sideline array
  - ▷ OASPL for all operating points and some OGV configurations
  - ▷ Power Levels (PWL) reconstructed from these microphone signals

Unsteady Flow Solution



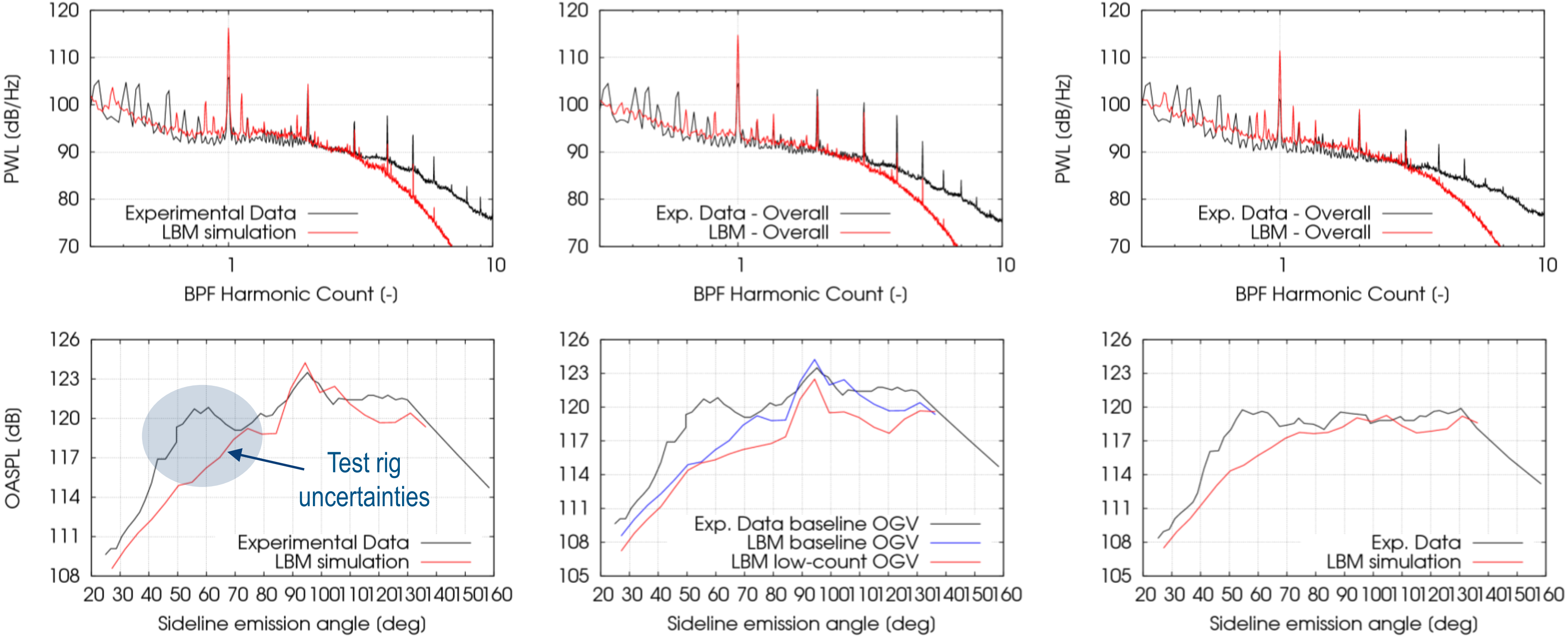


Far-field noise propagation



Power Levels & Directivity

Baseline | Low-Count | Low-Noise

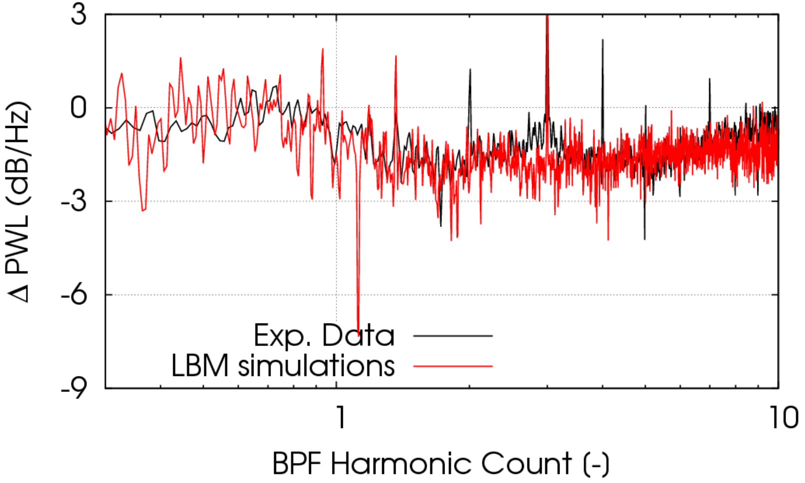


Test rig uncertainties

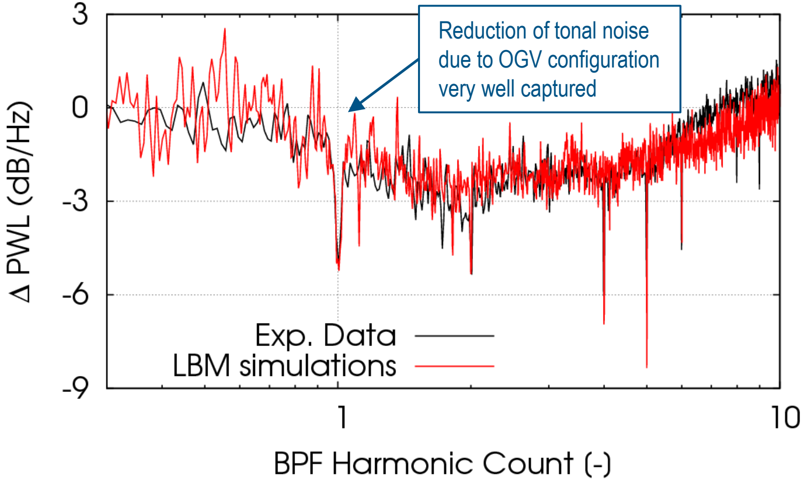
OGV Effect – Far-Field Acoustics

Δ PWL

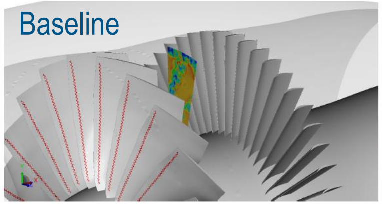
Low-Count – Baseline

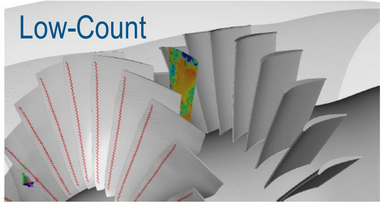


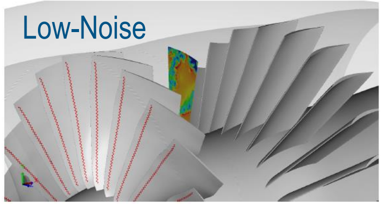
Low-Noise – Baseline



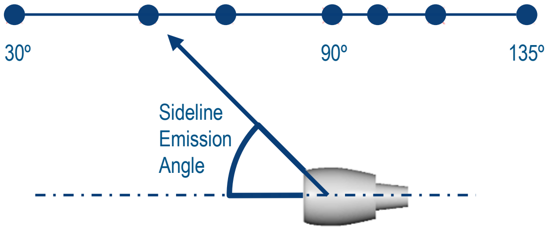
Reduction of tonal noise due to OGV configuration very well captured





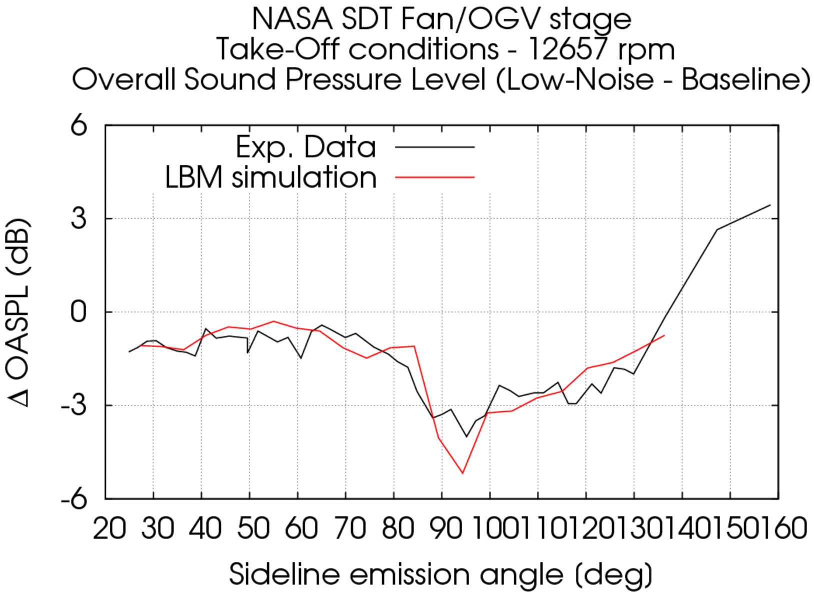


OGV Effect – Far-Field Acoustics

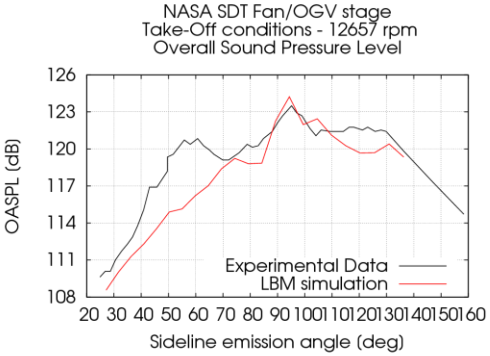


Δ OASPL

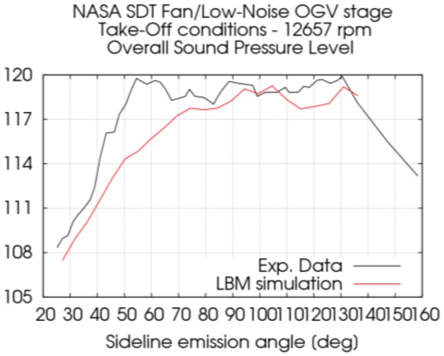
Low-Noise - Baseline

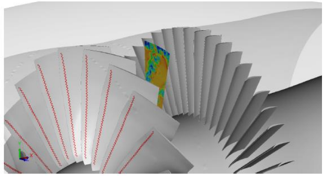


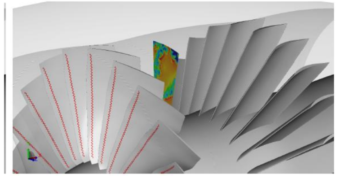
Baseline



Low-Noise

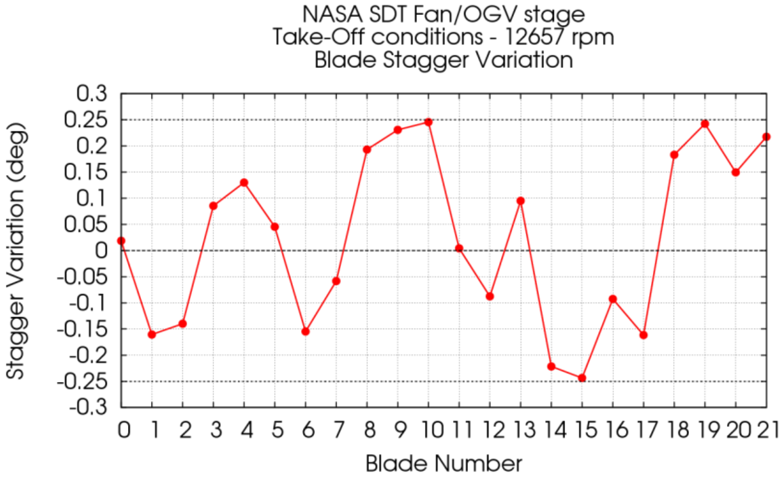






Multiple Pure Tones (MPT)

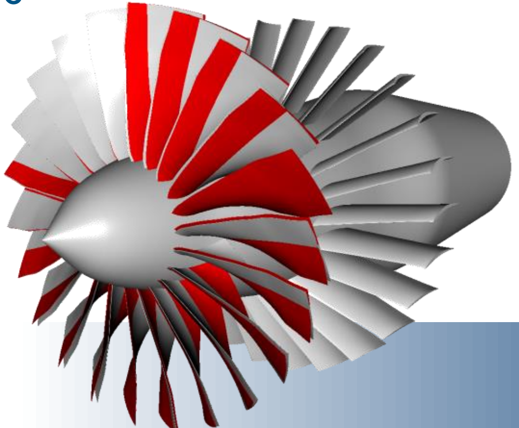
- Slight variations of the stagger angle between neighbor blades can produce MPT at transonic fan conditions
  - Simulate in PowerFLOW this stagger variation by imposing a random angle to each blade



Actual stagger angles not measured in wind tunnel tests.

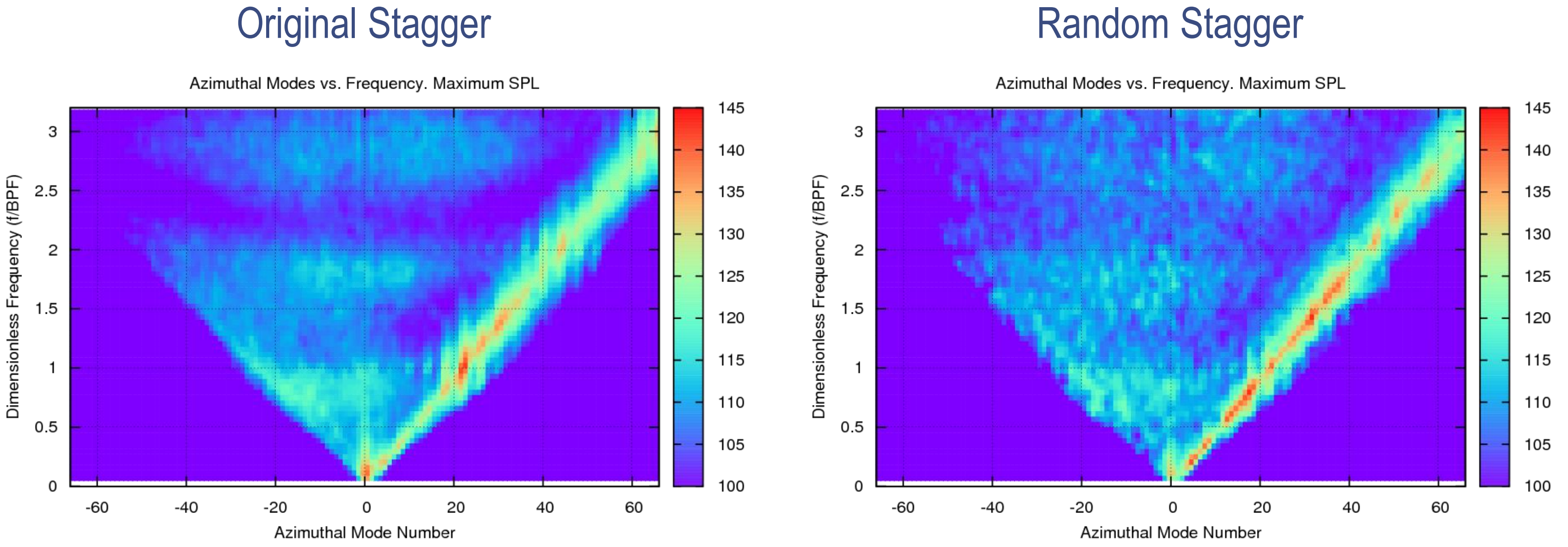
Random stagger angle distribution [-0.25 – +0.25] deg
This corresponds to an RMS of 0.25/sqrt(3) = 0.144 deg

Similar to what is suggested in literature:
Gliebe et al., “Aeroacoustic Prediction Codes”, NASA/CR 2000-210244



Original Stagger
Random Stagger (x40)

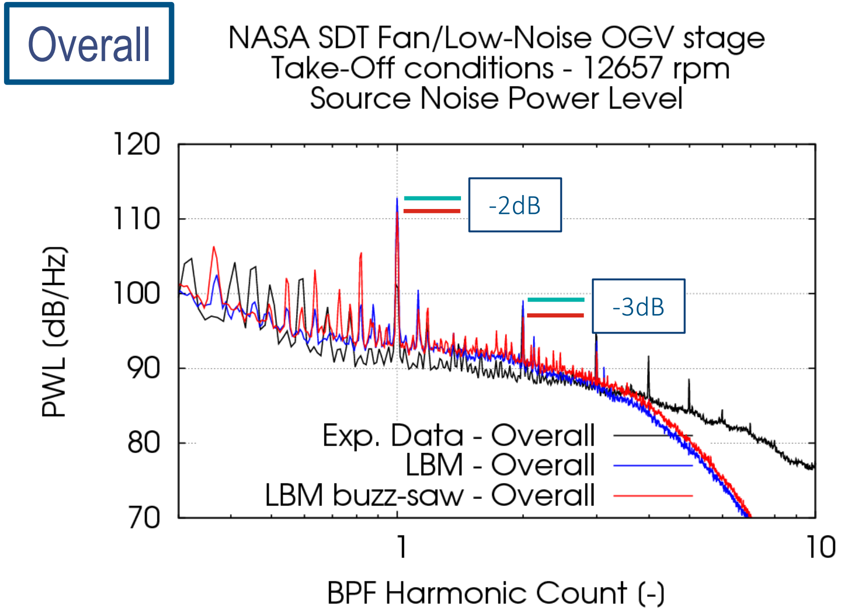
MPT – Modal Analysis

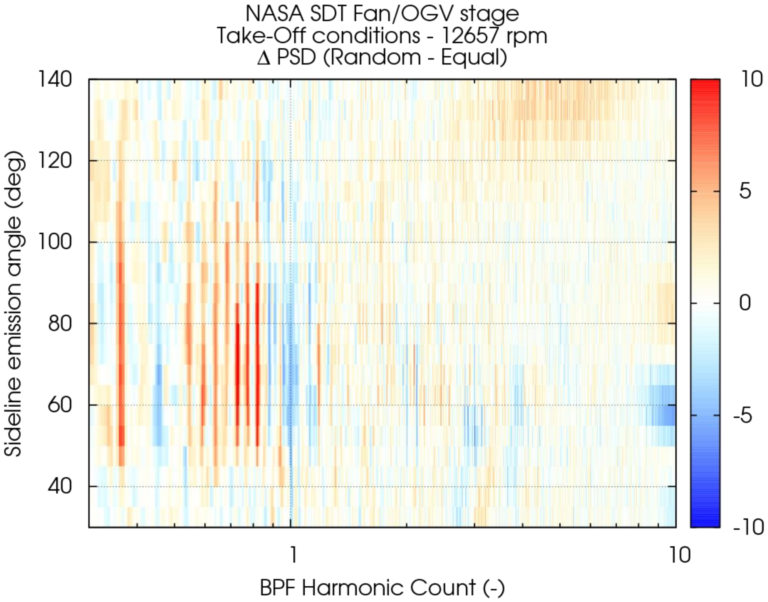


- Random stagger angles show higher positive modes in the line between +0 (at 0 frequency), +22 at BPF1, +44 at BPF2, etc.

MPT – Far-Field Acoustics

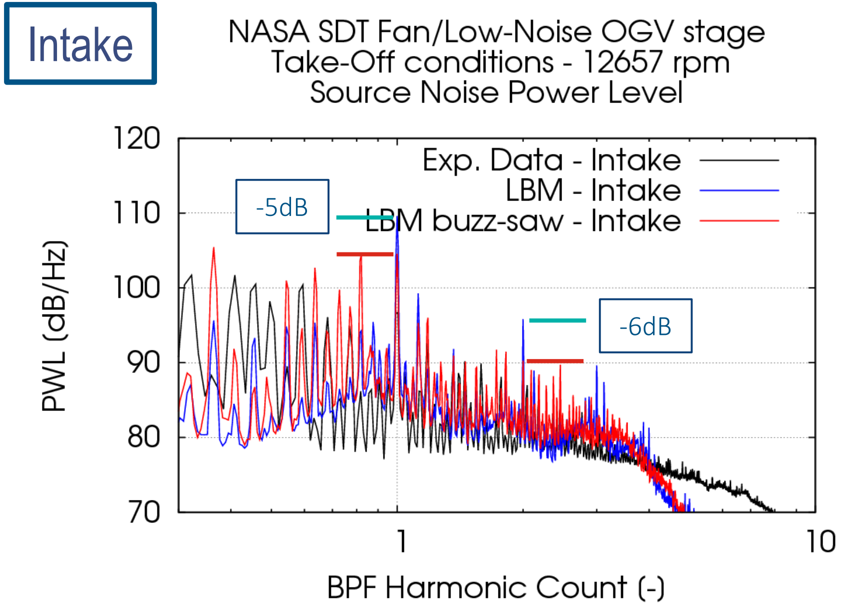
Overall



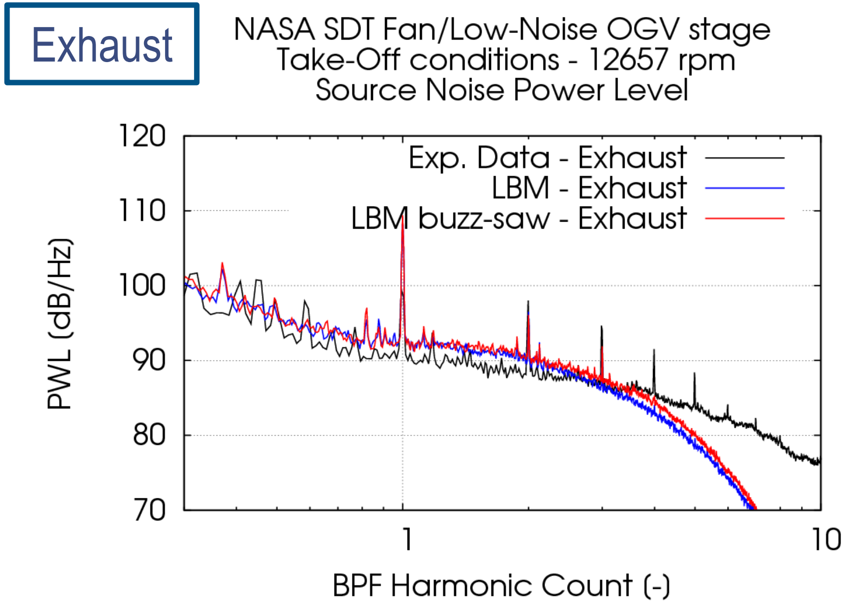


MPT – Far-Field Acoustics

Intake



Exhaust



Summary

- PowerFLOW solver is able to predict tonal and broadband noise of a fan stage at transonic conditions, in turn-around times compatible with industry cycles.
- Both, absolute and relative far-field noise levels have been predicted in the range of experimental uncertainty.
- Broadband noise generation mechanisms are less sensitive than tonal noise mechanisms to variability to the operating conditions and other uncertainties in the test rig.
  - In experiments, tones tend to present higher uncertainties (±4dB) than BB (±1dB).
  - Higher uncertainty from intake noise contribution (compared to exhaust) due to fan scattering of interaction noise
    - Small variations in blade stagger angles or fan RPM can induce this tone scattering
  - Consequently, it seems to be easier to predict consistently broadband than tonal noise
- In simulations, tones are much more sensitive than broadband to the setup variations:
  - BB mainly affected by geometrical modifications (i.e. the distance between fan blade tips and OGV tips)
  - BPF tone vary from 1 to 4dB depending on the grid strategy, blade stagger angles, etc…
- Outer radial areas of bypass flow are responsible for most of the noise:
  - Variations in wake depth and RMS at low radial stations have small impact on far-field acoustics
  - Tonal noise is quite sensitive to the fan shocks intensity and their relative position

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