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

Ignacio Gonzalez-Martino and Damiano Casalino
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:

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>% Design Fan Speed</th>
<th>Fan Tip Speed (m/s)</th>
<th>Fan RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach</td>
<td>61.7 %</td>
<td>228.1</td>
<td>7809</td>
</tr>
<tr>
<td>Cutback</td>
<td>87.5 %</td>
<td>323.6</td>
<td>11075</td>
</tr>
<tr>
<td>Sideline</td>
<td>100 %</td>
<td>369.8</td>
<td>12657</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Grid Resolution</th>
<th>Fan Tip Cell Size (mm)</th>
<th># Cells</th>
<th>Turn-Around Time (1000 cores)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>0.122</td>
<td>430 M</td>
<td>1 day</td>
</tr>
<tr>
<td>Fine</td>
<td>0.0915</td>
<td>885 M</td>
<td>2.5 days</td>
</tr>
<tr>
<td>Refined Rotor (x2 near-wall)</td>
<td>0.0915</td>
<td>953 M</td>
<td>5 days</td>
</tr>
</tbody>
</table>
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

![Graph showing fan pressure ratio vs. corrected inlet throat flow](image)

![Bar charts showing stage total pressure ratio and flow rate](image)
Instantaneous Flows

Relative Mach Number

Plane in the rotating frame

Pressure Time-Derivative
Shock Waves at Sideline Conditions

Experimental Data

DES**


LBM Simulation

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

- **LDV Station #1**
  - Better wake deficit prediction / equivalent width
  - $\langle u_x \rangle, \langle u_\theta \rangle, u'_x, u'_\theta$

- **LDV Station #2**
  - Increase in velocity RMS levels: closer to LDV data
  - $\langle u_x \rangle, \langle u_\theta \rangle, u'_x, u'_\theta$
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
Power Levels & Directivity

Baseline

Low-Count

Low-Noise

Test rig uncertainties
OGV Effect – Far-Field Acoustics

Reduction of tonal noise due to OGV configuration very well captured.
OGV Effect – Far-Field Acoustics

\[ \Delta \text{OASPL} \]

Low-Noise - Baseline

NASA SDT Fan/OGV stage
Take-Off conditions - 12657 rpm
Overall Sound Pressure Level (Low-Noise - Baseline)

\[ \Delta \text{OASPL} \text{(dB)} \]

Low-Noise

Baseline

Exp. Data

LBM simulation

Sideline emission angle (deg)
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 \text{ – } +0.25\] deg
This corresponds to an RMS of \(0.25/\sqrt{3} = 0.144\) deg

Similar to what is suggested in literature:
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

NASA SDT Fan/Low-Noise OGV stage
Take-Off conditions - 12657 rpm
Source Noise Power Level

Exp. Data - Overall
LBM - Overall
LBM buzz-saw - Overall

-2dB

-3dB

PWL (dB/Hz)

BPF Harmonic Count (-)

NASA SDT Fan/OGV stage
Take-Off conditions - 12657 rpm
Δ PSD (Random - Equal)

Sidelobe emission angle (deg)

BPF Harmonic Count (-)
MPT – Far-Field Acoustics

Intake

NASA SDT Fan/Low-Noise OGV stage
Take-Off conditions - 12657 rpm
Source Noise Power Level

Exhaust

NASA SDT Fan/Low-Noise OGV stage
Take-Off conditions - 12657 rpm
Source Noise Power Level
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