Simulation of Boundary Layer Ingestion Fan Noise for NOVA Aircraft Configuration

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Outline

• Background and motivation
• Numerical method
• Geometries and simulated cases
• Computational setup
• Numerical results
• Conclusions and future outlooks
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Background and motivation

• UHBR engines on next generation aircraft → Address increasingly stringent aviation regulations for pollution and noise impact
  - Enhanced propulsion efficiency and lower noise emissions
  - Integration challenges and special designs required
• Four different NOVA (Nextgen Onera Versatile Aircraft) aircraft geometries investigated at Onera with focus on engine integration options*

Background and motivation

- Boundary Layer Ingestion (BLI) configuration benefits
  - Mass and drag penalty reduction
  - Jet and wake losses reduction

- Many implications have to be addressed before deriving the associated benefits: effects of inlet flow distortion on engine efficiency, operability, aeromechanics and aeroacoustics

- Research goals:
  - To perform the first CFD/CAA simulation of a full aircraft+BLI fan stage system
  - To address BLI installation effects on fan noise for a NOVA BLI-like configuration

Potential fuel burn reduction
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Numerical method

- **SIMULIA PowerFLOW solver**:  
  - Lattice-Boltzmann method for subsonic/supersonic flows  
    - Solves the fully explicit, transient and compressible LBE  
    - Sliding mesh (LRF) for rotating geometries  
    - Hybrid solver: D3Q39 model inside LRF, D3Q19 model outside LRF  
  - LBM-VLES turbulence model  
    - Large-eddies are resolved (“coherent” statistically anisotropic eddies)  
    - Small eddies (statistically universal) are modeled with an extended RNG k-ε model  
    - Swirl term used to switch from modeled to resolved eddies  
    - Extended turbulent wall model to account for favorable/adverse pressure gradients

*Nie et al., “A Lattice-Boltzmann/Finite-Difference Hybrid Simulation of Transonic Flow”, AIAA 2009-139  
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Fan stage geometry

- Modified version of “Low-Noise” NASA/SDT*
  - Original geometry fully scaled to match NOVA fan diameter (2.15 m)
  - Original nacelle axial length increased to match NOVA BLI intake-fan distance (2.35 m)

*Envia, “Fan Noise Source Diagnostic Test - Vane Unsteady Pressure Results”, AIAA 2002-2430
Fan stage integration into NOVA fuselage

- Engine integration on NOVA lifting fuselage (courtesy of ONERA)
  - BLI engine
  - 40% buried intake
  - Intake-Fan distance = 2.35 m
  - Tilt angle = 1°
  - Toe angle = 2.5°

ONERA s-duct design constraints

- Semi-span = 19.05 m
- Fuselage length = 38.3 m
Simulated cases

- Isolated NASA/SDT with modified nacelle
- Installed NASA/SDT with modified nacelle into NOVA fuselage geometry

<table>
<thead>
<tr>
<th>Mach</th>
<th>Mach Tip</th>
<th>Pressure</th>
<th>Temperature</th>
<th>AoA</th>
<th>Glide angle</th>
<th>Tilt angle</th>
<th>Toe angle</th>
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<tbody>
<tr>
<td>0.25</td>
<td>1.0038</td>
<td>ISA at 1000 ft</td>
<td>4°</td>
<td>6°</td>
<td>1°</td>
<td>2.5°</td>
<td></td>
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</tbody>
</table>
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Computational setup

- Symmetry plane (at fuselage centerline)
- FWH permeable approach for far-field noise
- 16 Variable Resolution (VR) regions (medium grid resolution)
  - VR16: tip gap
  - VR15: leading/trailing edges of fan/OGV and nacelle lip
  - VR14: fan/OGV
  - VR13: bypass channel, nacelle and s-duct walls
  - VR12: FWH permeable surface
  - VR11-VR0: fuselage offsets and boxes up to domain boundaries
- Fan geometry rotated through LRF

<table>
<thead>
<tr>
<th>Grid Resolution</th>
<th>Fan Tip Cell Size (mm)</th>
<th># Cells</th>
<th>CPUh (10 revs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium*</td>
<td>0.355</td>
<td>611 M</td>
<td>56000</td>
</tr>
</tbody>
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Flow installation effects

• Instananeous flow on a plane normal to the fuselage
  – Higher flow acceleration at intake lip
  – Adverse pressure gradient induced flow separation on intake wall
  – Adverse pressure gradient induced flow separation on s-duct surface
  – Different fan wake/OGV interaction
Flow installation effects

- Mean flow on a plane upstream the fan
  - Strong flow distortion and non-uniformity
  - Flow acceleration in blade inboard regions
Fan blade sectional air-loads

- Phaselocked $c_x\bar{U}^2$ at three fan blade span-wise locations
  - **Inboard**: low-frequency unsteadiness $\rightarrow$ mean flow distortion
  - **Outboard**: high-frequency unsteadiness and lower mean value $\rightarrow$ turbulence ingestion

$$\bar{U} = \frac{u}{a_\infty}$$

**Local flow velocity**

**Freestream speed of sound**

$\bar{U}$ is the local flow velocity.

$u$ is the mean flow.

$a_\infty$ is the freestream speed of sound.

$\bar{U}$ is the mean flow.

Blade Inboard

Blade Outboard
Far-field noise directivity - Arc 0°

- PSD on 10 m radius arc centered around the fan center
Far-field noise directivity - Arc 45°

- PSD on 10 m radius arc centered around the fan center
Far-field noise directivity - Arc 90°

- PSD on 10 m radius arc centered around the fan center
Far-field noise – Mic at 20°/Arc 45°

- PSD for directivity angle of 20° on Arc at 45°
Far-field noise – Mic at 90°/Arc 45°

- PSD for directivity angle of 90° on Arc at 45°
Far-field noise – Mic at 160°/Arc 45°

- PSD for directivity angle of 160° on Arc at 45°
Band-pass filtered pressure around BPF1

- CFD computed pressure waves around BPF1
  - **Isolated engine**: low/high pressure areas extending upstream from each fan blade and co-rotating with fan propagate mainly upstream in the sideline direction
  - **BLI engine**: highly irregular pressure waves pattern propagating mainly upstream in the axial direction and downstream in the sideline direction
PNL on-the-ground

- Perceived Noise Level vs time during a takeoff flight path

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Isolated engine

BLI engine
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• LBM solver Simulia PowerFLOW used to address fan noise implications of NOVA BLI engine configuration

• Aerodynamic installation effects:
  – Flow distortion and non-uniformity $\rightarrow$ low-frequency air-loads variation
  – Separation on intake and s-duct walls $\rightarrow$ high-frequency air-loads variation

• Aeroacoustic installation effects:
  – Increase of noise sources intensity, but different propagation behavior
    • Isolated engine: noise radiated mainly upstream in the sideline direction
    • BLI engine: noise radiated mainly upstream in the axial direction and downstream in the sideline direction

• As future outlooks:
  – Analysis of boundary layer/fan interaction mechanisms
  – Analysis of fan wake/OGV interaction mechanisms
Thank you for your attention!