High Performance Computing for airfoil noise: present and future

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Airfoil noise is the canonical case of wall-bounded flows. All lifting surfaces on an airplane, such as wings, flaps, and control surfaces, are characterized by different flow regimes. For clean wings, the flow is typically laminar, whereas high lift devices and tail sections operate in transitional or turbulent regimes. The Reynolds number $Re_c \approx 10^6$ and Mach number $M \approx 0.3-0.8$ are indicative of these flow conditions.
Overall Background -2

Propulsion systems
Re_c \sim 10^6-10^7; M \sim 0.3-0.8

Ventilation systems
Re_c \sim 10^4-10^5; M \sim 0.05

Noise annoyances in daily life
Overall Background -3

Power generation noise
$Re_c \sim 10^6-10^7$; $M \sim 0.3-0.8$

Airframe noise (landing gear)
$Re_c \sim 10^6$; $M \sim 0.15-0.2$

With fairing
Airfoil Canonical Cases

Msc: L. Corriveau
PhD, Post-doc: J. Winkler
PhD, Post-doc: J. Christophe
PhD: J.C. Giret
Post-doc: M. Sanjose
On an airfoil, wall-pressure and loading fluctuations induced by a turbulent vortical field can be produced by several mechanisms:

- **Turbulence-interaction noise**
- **Trailing-edge noise**
  - (AIAA 2010-3804, 2011-2933, AIAA2012-2112)
- **Vortex shedding noise**
  - (AIAA 2010-3804, 2011-2933, AIAA2012-2112)
- **Tip noise**
  - (Boudet et al. AIAA 2010-3198)
- **Stall noise**
  - (AIAA 2009-3198)
Airfoil Noise Validation

Open-Jet Aeroacoustic Experiment in ECL Large Wind Tunnel

Airfoil chord length $\sim 10 \, \text{cm}$

$16 \, \text{m/s} \leq U_0 \leq 40 \, \text{m/s}$

Valeo CD and NACA12 airfoils, Flat Plate, V2 and V3 airfoils

Nozzle exit section $50 \, \text{cm} \times 25 \, \text{cm}$

Thickness 4% Camber 12°
CAA Methods

● Hybrid methods:
  - Detailed geometry and high-fidelity flow field (unsteady CFD).
  - Mostly incompressible simulations at low speed
  - Noise prediction in a second step resorting to an Acoustic Analogy.

● Direct methods:
  - Detailed geometry and high-fidelity flow field (unsteady CFD).
  - Compressible flow simulations only.
  - Mostly near-field simulations.
Hybrid Acoustic Prediction

- Solution to Ffowcs-Williams and Hawkings’ analogy (*free space Green’s function*) → Curle’s analogy for fixed airfoil:

\[ c_0^2 \rho'(\vec{x},t) = \frac{1}{4\pi} \frac{\partial^2}{\partial x_i \partial x_j} \int_{V(t)} \left[ \frac{T_{ij}}{R|1-M_r|} \right] dV \]

\[ -\frac{1}{4\pi} \frac{\partial}{\partial x_i} \int_{S(t)} \left[ \frac{p}{R|1-M_r|} n_i \right] dS - \frac{1}{4\pi} \frac{\partial}{\partial t} \int_{S(t)} \left[ \frac{\rho_0 V_n}{R|1-M_r|} \right] dS \]

- Other analogies used here:
  - Amiet’s model based on Curle’s analogy (*free space Green’s function*) with an unsteady airfoil response for a finite chord-length flat plate.
  - Ffowcs-Williams and Hall’ model based on Howe’s finite chord flat plate Green’s function.
Effect of the jet accounted for on both mean and fluctuating flow fields

Span $\sim 0.1\,c$
First Results on CD airfoil (8°)

Simulation of noise sources: LES on CD airfoil with Stanford (Affiliates 2003)

Streamwise velocity near surface \( y=11 \) at \( U/U_C=5.62 \)

5 million nodes for a 6 month to a year scalar run

IJA 2009
Flow topology on CD airfoil (8°)

Symmetric

Periodic

32 Cells

64 Cells

Both spanwise mesh refinement and periodic BC are creating smaller structures

3-12 million nodes for a 2-3 month parallel run (32-64 procs)

AIAA 2009-3196
Strong vorticity generation right at the leading edge

Recirculation bubble and reattachment triggering turbulent boundary layer

Weak vortex shedding

15°

Detailed flow topology nicely captured at various flow regimes

AIAA 2009-3196
Good overall agreement for all simulations
Same trend as experiment for all a.o.a

AIAA 2009-3196
Siegen experimental set-up

Acoustic measurements:

- Boundary-layer trip
- Microphone setup

NACA 6512-63
Careful selection of numerical parameters for transition
Effect of tripping thickness correctly captured

AIAA 2009-3197
Good overall prediction of acoustic pressure
Trailing edge noise responsible for added noise at high f
Compressible DNS Results ($Re_c \sim 10^5$)

DNS without tripping

DNS with IMBM tripping

261 millions of nodes for a week parallel run (4000-6000 procs)
NACA6512 DNS mean flow ($Re_c \sim 10^5$)

Wall pressure coefficient

- Very similar wall pressure loading
- Transition occurs almost at same position
- Very similar velocity profile near the trailing edge

BL velocity profile near TE

$\frac{u_n}{u_{ref}}$ vs $y_n$
NACA6512 DNS noise predictions

Wall-pressure fluctuations

Far-field acoustic pressure

Very similar wall pressure fluctuation near TE
Very similar trailing-edge noise based on Amiet’s acoustic analogy
Compressible DNS Results (Re_c \sim 10^5)

Very complex dilatation field w/o tripping
Additional noise source on PS reattachment point
Full set-up LBM compressible DNS

Lattice-Boltzmann Method

- Powerflow 4.3a
- Discrete Lattice-Boltzmann equation
- Compressible (low Mach number formulation)
- DNS resolution achieved in the first 3 VR
- 2D setups: 28 million cells
- 3D setup (nozzle): 12% C span length, 640 million cells

<table>
<thead>
<tr>
<th>Case</th>
<th>Phys. Time</th>
<th>CPU Time</th>
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<tbody>
<tr>
<td>2D set-ups</td>
<td>0.4 s</td>
<td>2,095 hrs</td>
</tr>
<tr>
<td>3D set-up</td>
<td>0.1 s</td>
<td>87,400 hrs</td>
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</table>

processors Intel Xeon X5560 @ 2.80GHz

AIAA 2011-2716
2D LBM Dilation fields ($\text{Re}_c \sim 10^5$)

- **Free Field**
  - Free-field similar to low $\text{Re}_c$ DNS
  - Cardioid shape of main trailing-edge noise
  - Diffraction effect of the nozzle lips captured
  - Weaker noise source at the bubble reattachment point

- **Nozzle**
3D LBM Dilation & velocity fields (Re_c ~10^5)

Much smaller flow structures on airfoil and wake
Strong vortex pairing in the jet shear layers
Dominant trailing edge mechanism
Almost no noise source at the bubble reattachment

640 million nodes for a 2 month parallel run (528 procs)
All LBM mean flow field ($\text{Re}_c \sim 10^5$)

Similar load for 2D and 3D LBM with nozzle
Very good agreement with wall pressure sensors
Excellent agreement of 3D LBM with HW
Only the wall-shear stress is over-estimated

| case                  | $\delta^*$ (
<table>
<thead>
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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>2D free-field</td>
<td>7 mm</td>
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<tr>
<td>2D nozzle</td>
<td>2 mm</td>
</tr>
<tr>
<td>3D nozzle</td>
<td>1.7 mm</td>
</tr>
<tr>
<td>MSU hot-wire</td>
<td>1.8 mm</td>
</tr>
</tbody>
</table>

MUSAF-II 2013
Overestimation in 2D due to too large vortical structures
Free-field: characteristic spectra of a detached flow (15°)
Excellent agreement of the 3D set-up
All unsteady simulations capture noise sources
Good direct noise prediction (Amiet good slope?)
High-lift device noise

- Good mean aerodynamic performances
- Noise radiation dominated by slat sources
Compressible LES of a rod-airfoil ($5 \times 10^5$)

LES of classical benchmark for airframe noise
Excellent overall agreement & noise source localization

AVBP

EXP.
AVBP FW-H Porous
AVBP FW-H Solid
Berland et al.
Eltaweel et al.

PSD [dB/Str]

0.01 0.1 1

EXP, ECL
LES Boudet
AVBP Coarse Mesh
AVBP Medium Mesh
AVBP Fine Mesh

0 2 4

-2 -4 -6

0.4 0.6 0.8 1.0

u/u_D

0 0.1 0.2

0

Exp. ECL
LES Boudet
AVBP Coarse Mesh
AVBP Medium Mesh
AVBP Fine Mesh

0 2 4

-2 -4 -6

0.0 0.1 0.2

u_{rms}/u_D
Conclusions

- Several CAA methods have been presented, combining both hybrid and direct noise simulations to yield airfoil noise.

- The hybrid method combining RANS simulations of the experimental set-up, incompressible LES on a restricted domain and an acoustic analogy has been very successful to yield trailing-edge noise in most situations (different operating conditions, tripping, blowing…). Presently nominal flow conditions can be solved efficiently this way.

- Yet some discrepancies still exist at high frequencies between the different formulations and feedback mechanisms cannot be captured (the Katana blade).

- Future HPC airfoil predictions will rely on compressible DNS for moderate speed cases ($Re_c \sim 10^5$) and LES for high speed cases ($Re_c \sim 10^6$). Lower speed cases yield too different flow physics.

- At low Mach number, detailed compressible LBM simulations seem to be a very efficient method to yield the direct noise signature in the actual test or installed conditions.

- More cores are needed for higher $Re_c$ on realistic geometries (blades)
Thank you
More Complex Cases

Low speed fans:
Msc, PhD: D. Lallier-Daniels
PhD: S. Magne
Post-doc: M. Sanjose

High speed fans:
Msc: L. Sauvageot, I. Kernemp
PhD: J. de Labordeirie
Post-doc: L. Soulat
Post-doc: H. Posson

Landing gear:
PhD: J.C. Giret
LES Prediction of landing gear noise

LAGOON1 configuration (Giret *et al.*, AIAA2013-2113)

Excellent overall agreement & noise source localization
Low speed fan wake topology

Iso-Q contours

Vortices wrap at blade cusp to form an energetic diverging spiraling vortex

Horse-shoe vortices connect

Small vortices in the tip clearance connecting to the hub vortex

a single vortex wraps around the ring with energetic vortex ejected in wake

Rich structures from both hub and tip clearance
CROR aerodynamic URANS results

Approach conditions on modern cropped CROR

Strong wake-interaction on R2 and potential interaction on R1
Strong tip and horse-shoe vortices: secondary sources
Good comparison with NASA experiment

Turb’flow

AIAA-2013-2058
LES of a reduced compressor stage

Q factor colored by vorticity magnitude

Mean pressure fluctuations

Pressure side

Turb’flow

Rotor blade SS transition triggered by adverse pressure gradient
Stator vane SS transition located at a fixed position (50% chord)
Main dipolar radiation at the leading edge

AIAA-2013-2042