Typical noise contribution breakdown for a long range Aircraft at approach:

- AIRFRAME ~50%
- JET
- TURBINE
- CORE
- FORWARD FAN
- REARWARD FAN

**Approach – AIRFRAME only**
- SLATS
- FLAPS
- CLEAN WING
- HTP
- NOSE L/G
- MAIN L/G

Noise generation mechanisms way more complex to capture than noise propagation to farfield ➔ Focus on sources
Enablers of Landing Gear noise High Fidelity simulation

Assessed with step by step validation

- Coupling / far-field acoustic radiation
- Advanced Boundary Conditions
- Wall modelling
- Turbulence modelling
- Numerical properties

SIMULATION ACCURACY

INDUSTRIAL READINESS

Assessed with seamless end to end workflow

- Maintenance, adaptability
- Solver Scalability
- Solver core Performance
- Physical mechanisms understanding
- Abilities on very complex Geometries

Assessed with step by step validation
Outline on Simulation accuracy

- Numerical approach overview
  - Lattice-Boltzmann Solver LaBS
  - Coupling with FWH solver
  - Numerical Setup & Grids

- Accuracy assessment
  - Mean & RMS Velocity fields comparison
  - $C_L$ and $C_D$ distributions
  - Wall pressure spectra comparison
  - Far field PSD & OASPL comparison

- Sensitivity analysis to num. parameters
  - Grid convergence
  - Subgrid scale model influence
  - Wall law model components

Relevant test case: simplified LGs «LAGOON»

Full study available in [AIAA2015–2993]
Outline on Industrial readiness

- Physical mechanisms understanding
  - Wheels inner cavity modes – LAGOON1
  - Tow bar vortex shedding – LAGOON2
  - Wheel rim caps removal – LAGOON3

- Corner stones towards industrial cases
  - Core performance & scalability
  - Flexible & Seamless meshing of complex configurations
  - Perspectives of applications on industrial configurations

Relevant test case: real A/C applications
LAGOON geometries & objectives

- Highly detailed experimental data
  - Aerodynamic Measurements (F2 Wind Tunnel)
  - Acoustic Measurements (CEPRA19 Wind Tunnel)
- 3 configurations of increasing complexity
  - LAGOON1 disclosed to NASA BANC III workshop, for accuracy & sensitivity assessment [Manoha_AIAA2015]
  - LAGOON2 & 3 used to cross compare geom. effects

  - **LAGOON 1**: Two wheels + Axle + Main Leg
  - **LAGOON 2**: + Tow bar + Lights + Steering actuator
  - **LAGOON 3**: + Torque link – Rim periphery caps

\[ M = 0.23 \]
\[ Re_{D_{wheel}} = 1.2 \times 10^6 \]
\[ D_{wheel} = 0.3 \text{ m} \]
\[ D_{leg} = 0.055 \text{ m} \]
\[ D_{axle} = 0.04 \text{ m} \]
Numerical Approach
Numerical Approach: LaBS solver

Lattice Boltzmann Solver (LaBS)
- 2010 – 2013 French collaborative project
- Led by Renault, Airbus, CS, Univ. Paris VI, ECL
http://www.labs-project.org/

- LaBS general numerical method
  - Classical LB approach, fully transient
  - D3Q19 BGK collision scheme, improved with regularization [Latt_MCS2006] [Ricot_2013]
  - Octree mesh refinement, specific treatment at resolution interface
  - Meshing embedded in the solver (and parallel!)

- LaBS numerical properties
  - Low Numerical dispersion & dissipation [Marié_JCP2009]
  - Excellent isotropy properties [Augier/Dubois_ICMMES2011]

- Augier & Dubois « Isotropy properties for lattice boltzmann schemes » ICMMES conference ,2012
Numerical Approach : Turbulence Modelling

- In-Flow Turbulence modelling
  - LES-LBM modelling using 2 possible subgrid-scale models
    - Subgrid scale model “Shear Improved Smagorinsky Model” [Leveque_JFM2007, Touil_PoF2013]

- Near-wall turbulence modelling
  - Immersed boundaries with Bounce-back principles [Chen/Doolen_IJNMF2014]
  - Wall Laws with pressure gradient effect [Afzal_IUTAM_Symposium1996][Malaspinas_JCP2014]

- Inlet & Outlet Boundary Conditions
  - Velocity imposed inlet & Pressure imposed outlet
  - Buffer zone as non-reflecting Boundary conditions [Xu/Sagaut_JCP2013] [Ricot_2013]

Numerical Approach: Grids

Setup
- LAGOON LG as installed in anechoic WTT (no ceiling wall)
- Constant velocity inlet & constant pressure outlet
- Simple setup (meshing directives through GUI)

Meshes
- Aim:
  Try to match the points distribution of a wall-modelled LES [Giret_AIAA2012] with fast turnover times
- Wake region: 2mm to 4mm (based on simple shapes)
- Near wall region: 0.4mm to 0.625mm (based on offsets of the geometry) ~ Y+ = 60
- Rough mesh convergence study
  COARSE: 20M nodes
  MEDIUM: 40M nodes
  FINE: 80M nodes
- CPU time on MEDIUM: 2 days on 360 core (0.32s physical time starting from scratch on intel XEON5-2697 @ 2.7Ghz)
Accuracy Assessment
Mean Axial Velocity : Plane Z = 0mm

Results provided to NASA BANC III workshop

- **Shear Layer thickness**
  - Too thick on COARSE mesh
  - Ok on MEDIUM mesh

- **Recirculation zone**
  - Size ok
  - Intensity ok

- **Wake shape**
  - Wake dimensions qualitatively satisfying
  - Better predicted by LBM than by LES
Mean Velocity profiles

- Excellent quantitative agreement
- Improvement with MEDIUM mesh in plane Z = -104 mm

X=160 mm

X=180 mm

X=220 mm

X=128 mm
RMS Axial Velocity : Plane Z = 0mm

- Shear on wheel flanks:
  - Size & intensity of Shedding well predicted on MEDIUM mesh (X=0.2 ; Y=0.15)
  - Results in good agreement with LES (AVBP)

- Results in good agreement with PIV despite some measurement artifacts
RMS Velocity profiles

- Fair quantitative agreement
- Improvement with MEDIUM mesh
- Subgrid scale contribution is NOT included

- xv=160 mm
- xv=180 mm
- xv=220 mm
- xv=128 mm

Flow direction

Rms Streamwise velocity (m/s)

PIV XV=160 Z=0
LaBS COARSE
LaBS MEDIUM
LES AVBP

PIV XV=180 Z=0
LaBS COARSE
LaBS MEDIUM
LES AVBP

PIV XV=220 Z=0
LaBS COARSE
LaBS MEDIUM
LES AVBP

PIV XV=128 Z=-104
LaBS COARSE
LaBS MEDIUM
LES AVBP

Landing Gear Noise Modelling – MUSAF III Colloquium
PSD at the wall: Wheel Rolling Band

- Low freq. filter in the experiments (0 – 200Hz)
- Tones @ 1KHz & 1.5kHz well captured

Landing Gear Noise Modelling – MUSAF III Colloquium
Gradual increase of PSD levels at the wall along with boundary layer development
PSD at the wall: Wheel Rolling Band

Pressure PSD (dB/Hz)

Frequency (Hz)

Kulite 5
LaBS COARSE
LaBS MEDIUM

PSD at the wall: Wheel Rolling Band
PSD at the wall: Wheel Rolling Band

- K7 corresponds to the detachment point due to GradP
- COARSE mesh predicts slightly earlier separation

![Graph showing PSD at the wall with frequency and pressure PSD axes.]

- Kulite 7
- LaBS COARSE
- LaBS MEDIUM
Flow fully detached at K8
Observation of cavity modes

LAGOON #1 Landing Gear Wall pressure fluctuations computed by LaBS

Pressure (Pa)

- 101000
- 100000
- 99000
- 98000
- 97000
- 96000
- 95000
- 94000
Observation of cavity modes

- FEM analysis conducted to cavity eigenmodes identification:
  - Mode @ 1048Hz
  - Mode @ 1529Hz

- Superposition of these 2 modes observed in the simulations
Shedding of the Tow Bar
Shedding of the Tow Bar

- Peak around 1100Hz on K1 & K2
- Emerging even more behind tow bar

Landing Gear Noise Modelling – MUSAF III Colloquium
Corner stones towards industrial cases
Performance & Scalability

- Single core peak performance of LBM algorithm much faster than classical N-S:
  - Faster than any FD schemes, way faster than FV approaches (Courtesy of Sagaut et al.)

<table>
<thead>
<tr>
<th>Numerical Approach</th>
<th>NS – O(2) Centered + RK3</th>
<th>NS – O(3) DRP Tam + RK3</th>
<th>NS – O(6) Lele + RK6</th>
<th>LBM BGK scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Flop/iteration</td>
<td>711</td>
<td>2862</td>
<td>11295</td>
<td>588</td>
</tr>
</tbody>
</table>

- Accuracy of LBM collision scheme [Ricot_JCP2009]
  - Almost equivalent to O(3) in terms of dispersion
  - Way better than any classical approaches, incl. O(6), in terms of dissipation

- Local time step (gift from octree mesh) yields additional performance benefits without the difficult compromises from implicit schemes

- Overall computational cost ~1µs/iteration/cell
  (7x to 10x faster than fastest NS explicit schemes)
Performance & Scalability

- Local algorithm, very suitable for massively parallel computing

- Constant performance, and efficient speedup

\[ \approx 80\% \text{ yet not perfect, due to the fast base algorithm} \]
Seamless meshing of complex configurations

- Geometrical details play a significant role in noise radiated (HF content).
- Real life configurations for LG noise are much more than complex !!!
  - Structured meshes have given up
  - Unstructured becomes very tricky
  - Immersed octree takes the lead
Seamless meshing of complex configurations

- Meshing done in parallel by the solver
- Example without any wake refinement
- Every second cell displayed
Seamless meshing of complex configurations

- Scaling up seamlessly
- Every second cell displayed
Perspective of applications

- For acoustics purpose:
  - Real configurations can be finally investigated without hazardous simplifications (unknown impact in terms of physics)
  - Installation effects reachable
    - Velocity deficit due to wing circulation,
    - Interaction between LG, Flaps,
    - Influence of NLG wake…

- For wider purpose:
  - Steady loads
  - Unsteady loads
  - …
Conclusions
Conclusion & Lessons learned

Conclusions on accuracy of LBM

✔ Level of agreement observed:
  - Very satisfying on both Mean & RMS velocity fields & integrated aero quantities (not shown today)
  - Very good agreement on wall PSD

✔ Meaningful physical phenomena well captured
  - Gradual increase of wall PSD with BL development, then sudden change after detachment point
  - On LAGOON1, Cavity mode directly visible on time resolved wall pressure [Casalino2014] & [Giret2013]
  - On LAGOON2, Vortex shedding from tow bar perturbs this cavity mode and yields another peak (1100Hz)

✔ However, everything is not yet perfect in current approach
  - Wall laws / near wall treatment
  - Parler des limites des transitions

Conclusions on industrial readiness

Engineer’s daily life game changer wrt unsteady well established NS-CFD methods

✔ Real A/C geometry without simplification

✔ Automatic/Flexible Billion cells mesh if needed

✔ 1000+ core scalable on HPC

✔ Turnaround time breakthrough

Next step
Take full benefit of LBM techniques for other industrial applications of interest.
Thank you for your attention!

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