Application of Lattice Boltzmann Method in automotive industry with focus on aeroacoustic simulations

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with contributions of:

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Outline

- Some aeroacoustic problems in automotive industry
- LB schemes for computational aeroacoustics
- Example of aeroacoustic simulations with EXA/PowerFLOW
- Aerodynamic drag simulations
Aeroacoustic problems

- **Interior noise aeroacoustics**
  - Broadband noise with, sometimes, unwanted frequency peaks
  - Relevant frequency range: all the audible spectrum (20 Hz → 10 kHz)

Example of interior aeroacoustic noise spectra

Noise generated by HVAC outlet vent
Automotive aeroacoustics

- **“External” aeroacoustics**
  - Both aerodynamic (incompressible) and acoustic (compressible) pressure fluctuations contribute to interior wind noise
  - Acoustic wall pressure fluctuations are much less energetic than aerodynamic pressure but much more efficient in term of panel excitation

- **“Internal” aeroacoustics**
  - Source and propagation in ducts (HVAC, inlet and exhaust engine ducts)
  - Fan noise, aerodynamic noise generated by flow through ventilation outlets
Automotive aeroacoustics: cavity noise

- **Sunroof buffeting**
  - Strong acoustic/aerodynamic coupling between vortex shedding in the opening and acoustic resonance of the passenger compartment

- **Door gap noise**
  - Door gap: small slots between car body and doors
  - Weak coupling between the broadband external turbulent excitation and the cavity resonance
Computational AeroAcoustics: hybrid and direct approaches

Steady CFD: mean aerodynamic field only

Unsteady CFD for incompressible flows: aerodynamic field only

Direct Noise Computation: unsteady compressible flow with "high-order" schemes: aerodynamic + acoustic fields

Turbulent field models: (synthetic turbulence, semi-empirical models)

Acoustic source models: (Lighthill analogy, ...)

Propagation model or solver: (integral methods, linear acoustics solver (FEM/BEM), linearized Euler equations solver (mean flow effect on propagation)

Acoustics pressure field
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Acoustics pressure field

Very difficult for real (complex) flows (OK for homogeneous turbulence, axi-symmetric jets,...)
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Acoustics pressure field

How to define the source region?

How to calculate the acoustic pressure inside the source region itself?

Only acoustic/flow weak coupling
Computational AeroAcoustics: hybrid and direct approaches

Direct Noise Computation:
unsteady compressible flow
with « high-order » schemes:
aerodynamic + acoustic fields

Acoustics pressure field
Example of direct noise calculation with LBM

- In-house D2Q9 model (BGK)
- Non-reflecting boundary conditions
- Selective viscosity filter for stability control

\[
\text{Ricot D., Maillard V., Bailly C.,} \\
\text{AIAA paper 2002-2532}
\]

\[
\text{Mach} = 0.25 \\
\text{Re}_L = 8 \cdot 10^3 \\
St = fL / U_0 = 0.89 \\
\text{(Rossiter mode 2)}
\]

In agreement with other CAA simulations performed with optimized finite difference Navier-Stokes codes (Gloerfelt, 2001, Rowley, 2002)

Other examples:
von Neumann analysis

Linearization of the equilibrium function around a uniform mean flow:

\[ f_{\alpha}^{eq} \left( f_{\alpha}^{(0)} + f_{\alpha}' \right) \]

\[ f_{\alpha}^{eq} = \rho \omega_{\alpha} \left( 1 + 3u_c + \frac{9(u_c)^2}{2} - \frac{3|u|^2}{2} \right) \]

Search for the plane wave solutions of the linearized equation:

\[ f_{\alpha}' = \hat{A}_{\alpha} \exp[i(k \cdot x - \omega t)] \]

Eigenvalue/eigenvector problem:

\[ \text{DVBE – BGK:} \quad \frac{\partial f_{\alpha}}{\partial t} + c_{\alpha,i} \frac{\partial f_{\alpha}}{\partial x_i} = -\frac{1}{\tau} [f_{\alpha} - f_{\alpha}^{eq}] \]

\[ \Rightarrow \quad i\omega f' = M^{\text{DVBE}} f' \]

\[ \text{LBM – BGK:} \quad g_{\alpha}(x + c, t + 1) = g_{\alpha}(x, t) - \frac{1}{\tau_g} (g_{\alpha}(x, t) - g_{\alpha}^{eq}(x, t)) \]

\[ \Rightarrow \quad e^{-i\omega} g' = M^{\text{BGK}} g' \]

\[ \text{LBM – MRT:} \quad g(x + c, t + 1) = g(x, t) - P^{-1} S[m(x, t) - m^{eq}(x, t)] \]

\[ \Rightarrow \quad e^{-i\omega} g' = M^{\text{MRT}} g' \]

Velocity model: D3Q19
Discrete Velocity Boltzmann Equation

Ma = 0.2

Dispersion

DVBE: strictly exact in term of dispersion

Dissipation

DVBE: small error in the dissipation due to the $M^3$ error term
LBM-BGK and LBM-MRT

Dispersion

- Theoretical
- BGK
- MRT

Dissipation

- BGK acoustic modes
- BGK & MRT shear modes

MRT acoustic modes

Overdamping of acoustic modes compared to the «physical» dissipation (bulk dissipation ~ shear dissipation)

BGK & MRT: same dispersion error
Von Neumann analysis applied to Navier-Stokes schemes

Linearized Navier-Stokes equations:

\[
\frac{\partial \mathbf{U}'}{\partial t} + \frac{\partial}{\partial x_1} [E'_e - E'_v] + \frac{\partial}{\partial x_2} [F'_e - F'_v] + \frac{\partial}{\partial x_3} [G'_e - G'_v] = 0
\]

Euler terms \hspace{1cm} \text{viscous terms}

Finite difference schemes:

\[
\frac{\partial \mathbf{U}}{\partial x_i}(x_i^0) = D_i(x_i^0) = \frac{1}{\Delta x_i} \sum_{j=-N}^{N} a_j \mathbf{U}(x_i^0 + j \Delta x_i)
\]

Runge-Kutta time marching schemes:

\[
\mathbf{U}^{n+1} = \mathbf{U}^n + \sum_{j=1}^{p} \gamma_j \Delta t^j F^j(\mathbf{U}^n)
\]

Eigenvalue/eigenvector problem:

\[
e^{-i\omega} \mathbf{U}^n = \mathbf{M}_{d}^{NS} \mathbf{U}^n
\]
Comparison LBM vs finite difference Navier-Stokes schemes

- **LBM has**
  - lower numerical dissipation than all aeroacoustic-optimized schemes
  - lower dispersion error than FD of order 2 in space and 3 in time (Runge-Kutta)
  - higher dispersion error than FD of order 3 in space and 4 in time (Runge-Kutta) and DRP (Dispersion Relation Preserving) optimized 6th order schemes
Comparison LBM vs finite difference Navier-Stokes schemes

- DRP Navier-Stokes schemes need lower number of points per wavelength than LBM to achieve a given accuracy... but their computational cost is much higher
  - Number of floating point operations per time-step of LBM is lower than that of 2th order FD schemes...
- For a given problem (target accuracy and given simulated physical time), the computational cost of Navier-Stokes schemes strongly depends on the CFL (time-step)
- For CFL ~ 1 (explicit schemes), the total simulation cost of Navier-Stokes schemes is higher than LBM


- Same conclusions with industrial Navier-Stokes (Finite volume) code:
  - Industrial comparison of PowerFLOW vs Fluent-DES at PSA Peugeot-Citroen (see [http://www.gdr2493.cnrs-mrs.fr/IMG/pdf/M-Pachebat-PSA.pdf](http://www.gdr2493.cnrs-mrs.fr/IMG/pdf/M-Pachebat-PSA.pdf))
How to use LBM in an industrial framework?

- **In-house / academic LBM codes**
  - VirtualFluids, TU Braunschweig
  - waLBerla, Univ. Erlangen, Nuremberg
  - International Lattice Boltzmann Software Development Consortium, Univ. Of Amsterdam, NEC, HLRS Stuttgart,…
  - HemeLB, Center of Comput. Science, Univ. College London
  - …

- **Open Sources LBM codes**
  - OpenLB-Palabos, lead by EPF Lausanne, Switzerland
  - El-Beem (used in Blender for free surface flows), ETH Zurich, Switzerland
  - …

- **Commercial LBM software**
  - PowerFLOW, EXA Corp.
  - MetaCFD, MetaHeuristics, USA (consulting only ?)

- **Industrial software**
  - LaBS (Lattice Boltzmann Solver), French industrial and academic Consortium
LaBS : Lattice Boltzmann Solver

Partners :

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- Three-year project (2009-2012) funded by the french ministry of industry and the region Iles de France with support of competitiveness clusters:
  - Lattice Boltzmann Method
  - Large Eddy Simulation approach
  - Optimization for massively parallel computing
  - Simultaneous simulation of aerodynamic noise sources and their acoustic propagation
PowerFLOW – current version

- LBM D3Q19 BGK with some adaptations
- Immersed frontiers for complex geometry (volumetric formulation)
- Turbulence model
  - Modified (Yakhot & Orszag, not published) $k-\varepsilon$ RNG model (Yakhot & Orszag, 1986)
  - Modified (adverse pressure gradient effects) log-law wall model
- Stability control with turbulence model + threshold numerical viscosity
- Parallel computations
  - Tens of millions of cells calculated for hundreds of thousands of time-steps on tens of CPU in a few days
Acoustic impedance of outlets, without mean flow

- Simulation without mean flow (only “acoustics”)
- Validation of the acoustic behavior of the HVAC outlet

(J.-L. Adam et al., Acoustics’08, Paris)
Aerodynamic noise generated by HVAC vents

\[ U_0 = 18 \text{ m/s} \]

(J.-L. Adam et al., Acoustics’08, Paris)

Upstream acoustic pressure

Downstream acoustic pressure

\[ \text{Vorticity snapshot} \]
Direct aeroacoustic source identification based on LBM and beamforming technique

(J.-L. Adam et al., 2009, AIAA paper 2009-3182)

- Measurements in the aeroacoustic wind tunnel S2A
- Source detection with microphone array associated with beamforming algorithm

- Maximum mesh resolution around side mirror and A-pillar
  - Complete fine mesh around the whole car is impossible with our CPU capabilities
  - Coarser mesh around wheel house, rear of the car,…
  - only very low frequency turbulent structures are simulated in these regions

- Source detection with “virtual” microphone array measurements associated with the same beamforming algorithm as that used in wind tunnel
Direct aeroacoustic source identification based on LBM and beamforming technique

1/3 octave band 1000 HZ

1/3 octave band 1600 HZ

Spatial integration of acoustic power around the side view mirror

Simulation
Experiments

Power dB

Frequency (Hz)

10 dB
Aerodynamic drag simulation

- **Objectives**
  - Drag and lift coefficient calculation → design choice to minimize CO$_2$ emission
  - Shape and detail optimizations

“3D” wake (strong longitudinal vortices) → High drag

“2D” wake → Low drag

*S. Parpais, Renault R&D mag., 2003*
Validation of aerodynamic drag simulation

- First validations on simplified car (2002)
  - No underhood
  - Flat underbody

Measurements

PowerFLOW

Total pressure loss 10 mm downstream the simplified car
Validation of aerodynamic drag simulation

- **Validation on Megane CC**
  - No underhood flow
  - Fully detailed underbody

![](image1.png)

**PowerFLOW**

**Measurements**

Normalized (Ux / U0) longitudinal mean velocity in the symmetry plane
Validation of aerodynamic drag simulation

- **Validation on Megane CC**
  - Drag and lift coefficients are well recovered within few percents

**Total pressure loss in the Megane CC wake**
Underhood flow

- Heat exchanger are modeled with equivalent porous media
- Fan model
  - Fixed fan
  - Rotating fan using Multiple Reference Frame approach

- Experimental validation based on PIV measurements

O. Bailly et al., SIA, Lyon 2005
Validation of aerodynamic drag simulation with underhood flow

PowerFLOW

Measurements

Total pressure loss in the Scenic wake
Concluding remarks

- LBM errors only come from space and time discretizations: velocity discretization is (nearly) exact
- In its standard form, MRT models seem to not improve the dispersion accuracy
  - Be careful with the bulk viscosity increase that allows better stability but that overdamps acoustic waves
- Even if the convergence rate of LBM is only second order, the absolute error of LBM for a given mesh is much lower than that of second order Navier-Stokes schemes
- LBM is competitive with high-order and optimized DPR Navier-Stokes schemes because the same accuracy can be obtained with lower computational cost

- Very encouraging results are obtained with LBM/PowerFLOW on real industrial configurations for direct simulation of aeroacoustics problems
  - Direct Noise Calculation is the ideal strategy to simulate all automotive aeroacoustic problems
  - Simulations are still limited in term of frequency range: optimized turbulence/stability control models associated with improvement of numerical efficiency are needed in order to achieve higher frequency components
- Thanks to its numerical efficiency and low dissipation, LBM is a “perfect” scheme for LES/DES approaches
  - Full unsteady simulations performed for aerodynamic drag calculation with PowerFLOW seem to be a key point to obtain good results on a wide class of vehicle configurations