Application of Lattice Boltzmann Method in automotive industry

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Introduction

- In automotive industry: commercial codes « only »
- Only one commercial LB code: PowerFLOW (EXA Corp.)
- EXA Corp. created in 1991 by K. Molvig (MIT) and his PhD student (C. Teixeira)
- First commercial version of PowerFLOW around 1997, with support of Ford
- First use at Renault in 1998 for aerodynamics and aeroacoustics benchmarks (comparisons with other commercial CFD codes)
- Today, at Renault
  - Aerodynamics simulation (drag prediction)
  - External and internal aeroacoustics
  - Thermal management (since ~2006)
- Great success in ground transport industry
  - Automotive: Ford, BMW, Audi, Toyota, Nissan, Hyundai, PSA, Volkswagen…
  - Heavy/commercial vehicles: Scania, Volvo Trucks, MAN,…
  - Rail transport industry: Alstom, SNCF, …
Presentation outline

- **Specific models in PowerFLOW**
  - Multiscale mesh
  - Immersed boundary model
  - Turbulence model
  - Numerical stability management

- **Aerodynamic applications**
  - Validation on simplified car
  - Megane CC without underhood flow
  - Scenic with underhood flow

- **Aeroacoustic applications: direct noise calculations**
  - Theoretical results
  - Noise generated by ventilation outlets
  - Noise radiated by a fence-cube academic configuration
Successive LB models in PowerFLOW

- **First version of PowerFLOW (…2002) : D4Q54 (thermal model)**
  - 16-bits (integer) variables
  - MRT-like model (variable Prandtl number)
  

- **Second version of PowerFLOW (2002…2006) : D4Q34 (thermal model)**
  

- **Last version of PowerFLOW (2006…) : D3Q19 (SRT-BGK model)**
  - single precision floating point variables (32 bits)
  - convection/diffusion thermal equation solved with Lax-Wendroff FD scheme + Boussinesq approximation
  
  *Li, Y. & al., JFM, 2004

Order 3 : theoretically not necessary

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**Order 3**

Cette relation, utilisée dans le cadre de la théorie de Boussinesq, est souvent nécessaire pour obtenir des résultats précis en simulation numérique. Cependant, dans certaines situations, comme celles liées à la turbulence ou à des phénomènes de convection intense, l'ordre 3 peut ne pas être indispensable. Plus précisément, certaines simulations peuvent être effectuées correctement avec un ordre 2 de précision, ce qui réduit la complexité et les coûts de calcul. Il est donc important de s'assurer que l'ordre 3 est nécessaire pour une application spécifique avant de l'intégrer dans le modèle. La nécessité de l’ordre 3 dépend des conditions et des contraintes spécifiques de chaque cas d’étude.
Multiscale mesh

Continuity of speed of sound: \[ \Delta x_1 = 2 \Delta x_2 \quad \Delta t_1 = 2 \Delta t_2 \]

Continuity of viscosity: \[ \bar{\tau}_2 = \frac{1}{2} + n \left( \bar{\tau}_1 - \frac{1}{2} \right) \]
Multiscale mesh : volumetric formulation

\[ N^c_\alpha (\bullet) = g_\alpha (\bullet) \cdot V^c \]

- Fine \(\rightarrow\) Coarse : coalesce the eight fine volumetric distribution functions
- Coarse \(\rightarrow\) Fine : explode the coarse volumetric distribution function
- No rescaling of distribution functions
- No time-interpolation

Immersed boundary model for complex geometry meshing
Boundary condition on complex geometry (volumetric formulation)


- Outward distribution function flux for surface element $i$

$$\Gamma_{i}^{\alpha,{\text{out}}}(t) = \sum_{\bar{x}_k = 0} V_{i}^{\alpha}(\bar{x}_k)g_{\alpha}(\bar{x}_k,t)$$

- No-slip boundary condition

$$\Gamma_{i}^{\alpha,{\text{in}}}(t) = \Gamma_{i}^{-\alpha,{\text{out}}}(t)$$

- Wall boundary condition with a prescribed friction force (turbulence wall model)

$$\Gamma_{i}^{\alpha,{\text{in}}}(t) = -\Gamma_{i}^{-\alpha,{\text{out}}}(t) - \frac{1}{2\theta} C'_{i} u_{i}^{\alpha}(\bar{c}_{\alpha} \cdot \bar{n}_{i}) (g_{\alpha}^{eq,i}(t) - g_{-\alpha}^{eq,i}(t)) + ...$$

Friction force:

$$F_{i}^{\alpha}(t) = -C'_{i} \rho u_{i}^{\alpha} / 2$$

$u_{i}^{\alpha}$ tangential velocity in the first cell above the surface element $i$

$C'_{i}$ local friction coefficient
Turbulence modeling in PowerFLOW

- **Standard approach**: \( \tau \rightarrow \tau_{mol} + \tau_{turb} \)

- **Calculation of \( \tau_{turb} \) using a \( k - \varepsilon \) model**:

\[
\begin{align*}
\rho \frac{\partial k}{\partial t} + \rho \vec{u}_i \frac{\partial k}{\partial x_i} &= \frac{\partial}{\partial x_i} \left[ \left( \frac{\mu}{\sigma_k} + \frac{\mu_T}{\sigma_{kt}} \right) \frac{\partial k}{\partial x_i} \right] + \tau_{ij}^r S_{ij} - \rho \varepsilon \\
\rho \frac{\partial \varepsilon}{\partial t} + \rho \vec{u}_i \frac{\partial \varepsilon}{\partial x_i} &= \frac{\partial}{\partial x_i} \left[ \left( \frac{\mu}{\sigma_\varepsilon} + \frac{\mu_T}{\sigma_{\varepsilon T}} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{\varepsilon_1} \frac{\varepsilon}{k} \tau_{ij}^r S_{ij} - \left[ C_{\varepsilon_2} + C_\mu \frac{\tilde{\eta}^3 (1 - \tilde{\eta}/\eta_0)}{1 + \beta \tilde{\eta}^3} \right] \frac{\varepsilon^2}{k}
\end{align*}
\]

\( C_\mu = 0.085, \quad C_{\varepsilon_1} = 1.42, \quad C_{\varepsilon_2} = 1.68, \quad \sigma_k = \sigma_{kt} = \sigma_\varepsilon = \sigma_{\varepsilon T} = 0.719, \quad \eta_0 = 4.38, \quad \beta = 0.012 \)

\[ \tilde{\eta} = A \frac{k}{\varepsilon} |S| + B \frac{k}{\varepsilon} \Omega + C \frac{k}{\varepsilon} \left| \frac{\vec{u} \cdot \vec{\Omega}}{\varepsilon} \right| + ... \]

Modified (Yakhot & Orszag, not published) \( k - \varepsilon \) RNG model (Yakhot & Orszag, 1986)

- **« Swirl modification »**: \( \nu_T = C_\mu \frac{k^2}{\varepsilon} \frac{1}{1 + \tilde{\eta}} \)
Discretization of $k - \varepsilon$ equations

- Lax-Wendroff finite difference scheme on the same mesh
- Explicit time-marching scheme
- Small floor cut-off values and large ceiling values of $k$ and $\varepsilon$ to insure realizability of the turbulence quantities (for numerical stability)

- Near the wall: empirical boundary condition

$$k^+ = \frac{k}{u_*^2} = \frac{1}{\sqrt{C_{\mu}}} - e^{-0.1y^+} \left( \frac{1}{\sqrt{C_{\mu}}} + 0.29y^+ \right)$$

$$\varepsilon^+ = \frac{\varepsilon V}{u_*^4} = 0.04y^+ - 0.0033y^{+2} + \frac{1.04y^{+3}}{10^4} - \frac{1.04y^{+4}}{10^6}$$

Turbulence wall model

1. Extrapolation of the tangential fluid velocity $u_t$ from the inner domain variables

2. Calculation of $u_*$ with a modified log-law

$$
\frac{u_t}{u_*} = \frac{1}{\kappa} \ln \left( \frac{y^+}{\xi} \right) + B
$$

$$
\xi = 1 + g \left( L_{\text{char}}, \frac{\partial p}{\partial x_t} \right) \quad \xi > 1 \text{ if } \frac{\partial p}{\partial x_t} > 0
$$

( adverse pressure gradient effect)

$$
B = 5.0 \quad \kappa = 0.41
$$

3. Definition of a local friction coefficient and friction force

$$
C'_f = \frac{\rho u_*^2}{\rho u_i^2 / 2}
$$

$$
F_i = -C'_f \rho \frac{u_i^2}{2}
$$

4. Inject the incoming particle flux in order to obtain the friction force on each surface element $i$

$$
\Gamma^{\alpha, \text{in}}_i (t) = f \left( C'_f u_t \right)
$$
Numerical stability management

« Base viscosity » approach

- Imposed minimum value of the non-dimensional relaxation time

\[ \tilde{\tau} > \tilde{\tau}_{\text{base}} \quad \Rightarrow \quad \nu_{\text{eff}} = \nu + \nu_T > \nu_{\text{base}} (\Delta x) \]

- The base viscosity depends on the local mesh size \( \Delta x \)

In high turbulent viscosity region

\[ \nu_{\text{eff}} \approx \nu_T > \nu_{\text{base}} \]

But in low turbulent viscosity region (near wall separation for example)

\[ \nu + \nu_T < \nu_{\text{base}} \quad \Rightarrow \quad \nu_{\text{eff}} = \nu_{\text{base}} \quad \Rightarrow \quad \text{unphysical high level of viscosity} \]
Numerical stability management

Sunroof buffeting simulation
(D. Ricot, ECL, 2002)

Standard base viscosity

\[ \nu_{\text{eff}} = \nu_{\text{base}} \gg \nu + \nu_T \]  
neart flow separation

"Manually" reduced base viscosity

\[ \nu_{\text{eff}} = \nu + \nu_T > \nu_{\text{base}} \]
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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 validation on simplified car**
  - 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

![PowerFLOW](image1)

![Measurements](image2)

**Normalized \((U_x / U_0)\)** 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

![PowerFLOW vs Measurements](image)

**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

- Validation on Scenic
  - Fully detailed underbody
  - Underhood flow
Validation of aerodynamic drag simulation with underhood flow

**PowerFLOW**

**Measurements**

- **Ptot @ 10mm**
- **Ptot @ 700mm**
- **Ptot @ 1400mm**

**Total pressure loss in the Scenic wake**

Lattice Boltzmann scheme; Methods and Applications, CEMAGREF
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Aeroacoustic simulations

- **External aeroacoustics**
  - Both aerodynamic (incompressible) and acoustic (compressible) pressure fluctuations contribute to interior wind noise

- **Internal aeroacoustics**
  - Source and propagation in duct (HVAC)
  - Aerodynamic noise generated by flow through ventilation outlets

Lateral HVAC outlet of Twingo
Acoustic propagation with LBM: theoretical study

- Von Neumann analysis of the LB models
- Comparison with optimized finite difference Navier-Stokes schemes (DRP: Dispersion Preserving Relation)
  - 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)
  - ... but much lower computational effort in terms of number of floating point operations + compact scheme

Example of direct noise calculation with LBM

- In-house D2Q9 model
- Non-reflecting boundary conditions
- Selective viscosity filter

\[ Mach = 0.25 \]
\[ Re_L = 8 \cdot 10^3 \]
\[ St = fL/U_0 = 0.89 \]

(Rossiter mode 2)

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

Direct noise computation of a flow over cavity
Acoustic impedance of outlets, without mean flow

Acoustic reflection coefficient of a circular baffled open termination

![LBM simulation](image1)

![Acoustic reflection coefficient of a HVAC duct outlet](image2)

Analytical expression

LBM simulation

Sysnoise (BEM) simulation

LBM simulation
Noise generated by HVAC vents

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

Upstream acoustic pressure

Downstream acoustic pressure

(J.-L. Adam et al., Acoustics’08, Paris)
Fence-cube configuration (MIMOSA Project)

- $U_0 = 50$ m/s
- $dx_{\text{mini}} = 1$ mm
- 50 millions of cells

$(H. \ \text{Illy et al.}, \ DLES \ 2008)$

PowerFLOW

Snapshot of the $U_x$ velocity in the symmetry plane
Fence-cube configuration (MIMOSA Project)

Snapshot of the pressure field
(101328 < P < 101334 Pa)

Pressure level map on the microphone array for the third octave 315 Hz

LBM simulation

Measurements

dB scale
Concluding remarks

- **Other application fields**
  - Thermal management (underhood): two-way coupling between PowerFLOW (forced and natural convection) and RadTherm (solid conduction, radiation)
  - External aeroacoustics: simulation of wall pressure fluctuations (excitation of lateral windows and windshield by aerodynamic and acoustic pressure field)
  - Sunroof buffeting, effect of wind deflectors

- **Too dissipative turbulence model**
  - Frequency limitation for wall pressure fluctuation simulation
  - Better approach?: sub-grid model based on LES theory (*Dong et al., Phys. Fluid 2008*)

- **Numerical stabilization management with numerical viscosity**
  - Unphysical effective viscosity in some regions
  - Better approaches?: selective viscosity filter (*Ricot et al., ICMMES 2007*), MRT models, regularization method…

- **Single precision variable**
  - too high background noise in high frequency

- … **totally closed code**

- … **licence cost**