# Application of Lattice Boltzmann Method in automotive industry

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**with contributions of :**
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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)

*Chen, H. & al., Int. J. Modern Phys. C, 1997*

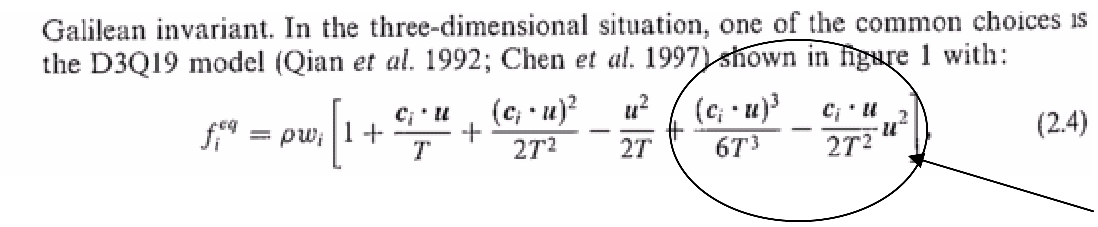
*US Patent 5848269, Chen, Hill, Hoch,*
*Molvig, Teixiera, Traub, 1995*

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

*Fan, H. & al., Phys. Rev. E, 2006*

- **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*

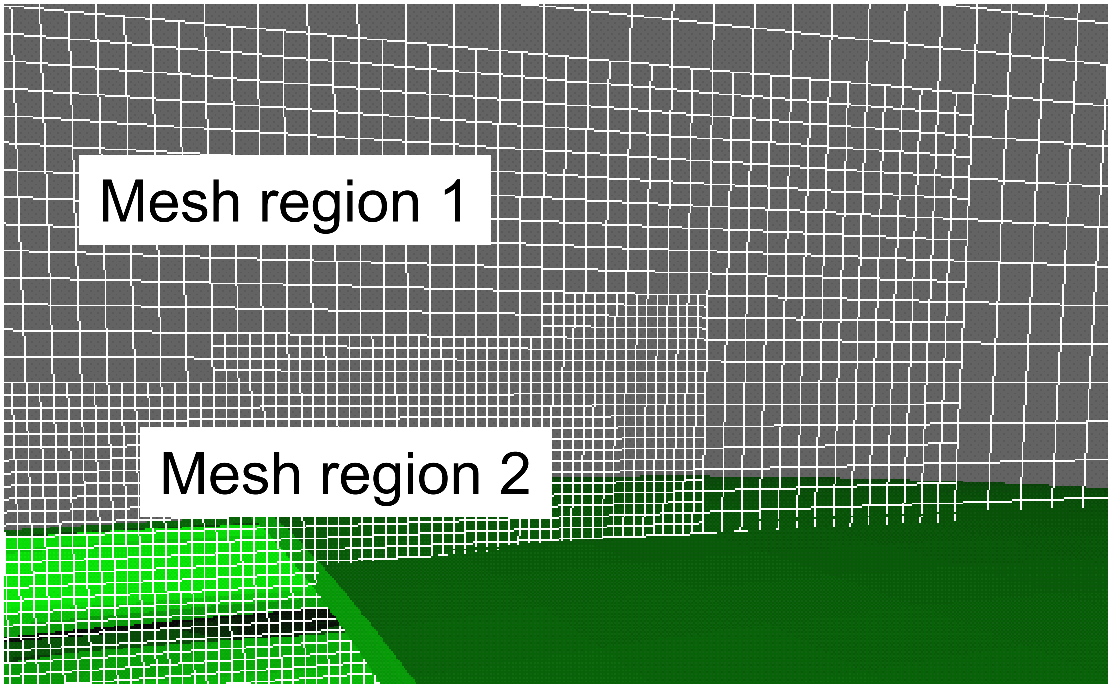


Galilean invariant. In the three-dimensional situation, one of the common choices is the D3Q19 model (Qian *et al.* 1992; Chen *et al.* 1997) shown in figure 1 with:

$$f_i^{eq} = \rho w_i \left[1 + \frac{c_i \cdot u}{T} + \frac{(c_i \cdot u)^2}{2T^2} - \frac{u^2}{2T} + \frac{(c_i \cdot u)^3}{6T^3} - \frac{c_i \cdot u}{2T^2} u^2\right], \qquad (2.4)$$

Order 3 : theoretically not necessary

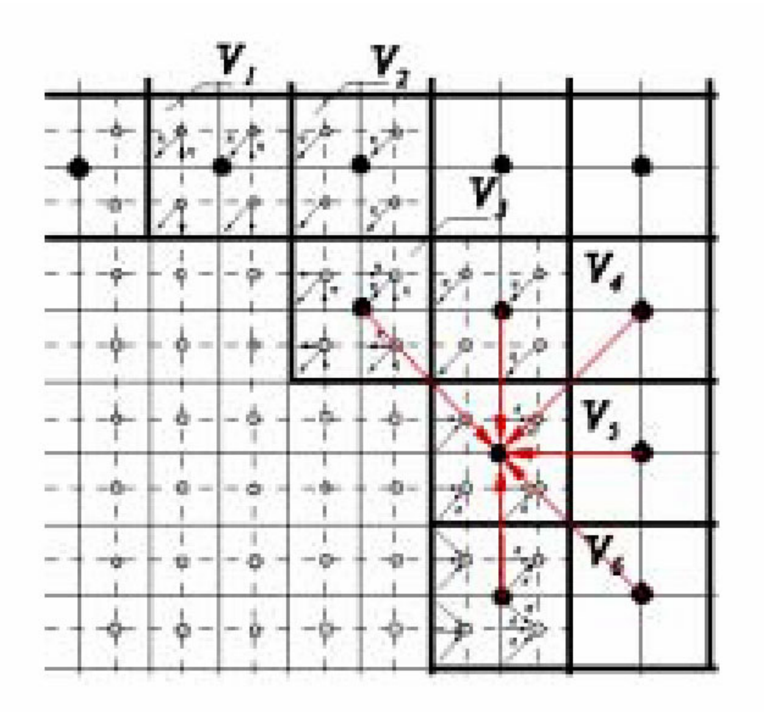
# Multiscale mesh



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

Continuity of viscosity : $\tilde{\tau}_2 = \frac{1}{2} + n\left(\tilde{\tau}_1 - \frac{1}{2}\right)$

# Multiscale mesh : volumetric formulation

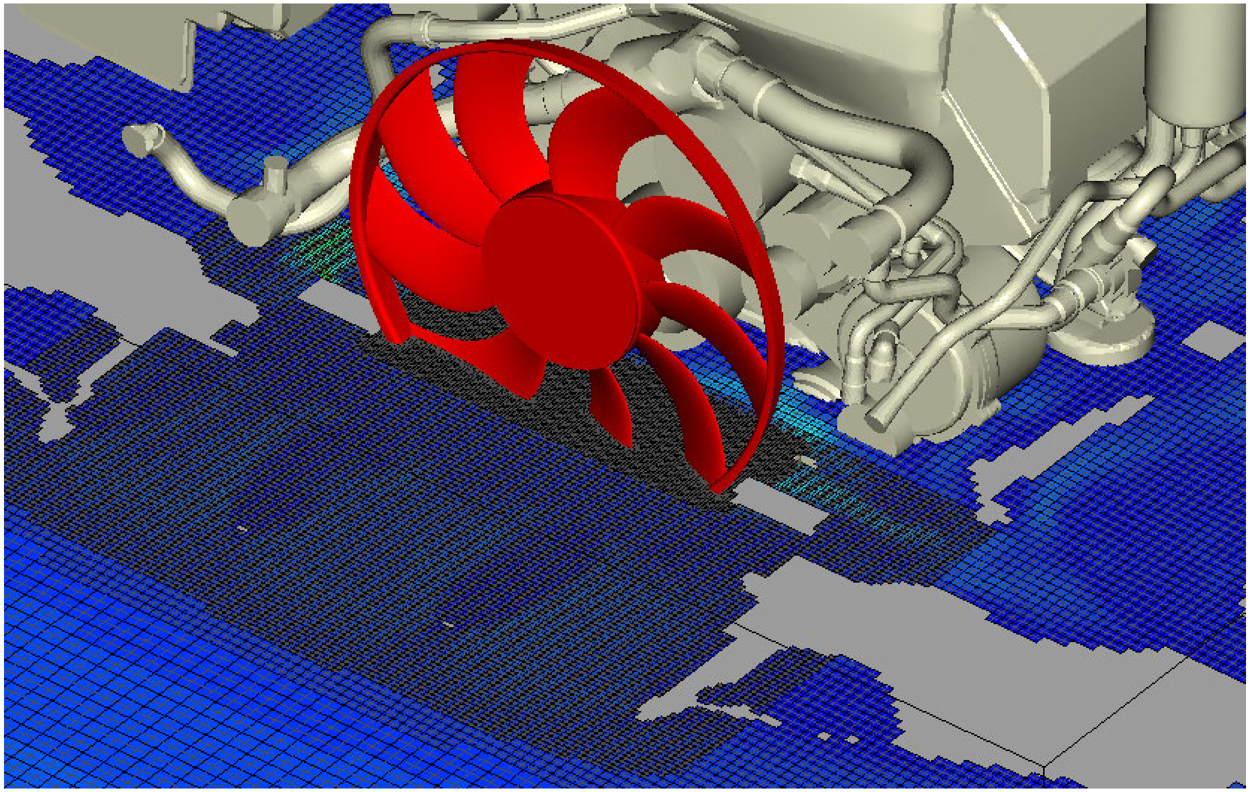


$$N_\alpha^c(\bullet) = g_\alpha(\bullet)\cdot V^c$$

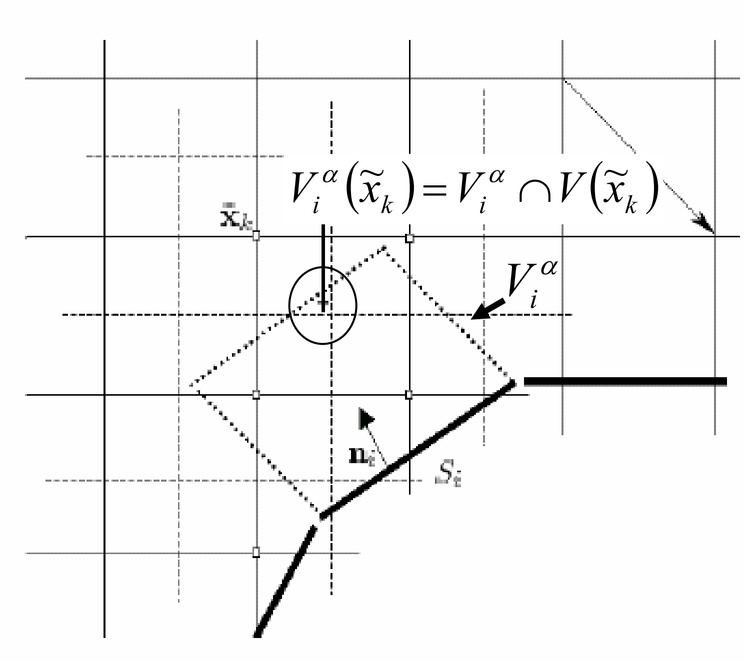
- **Fine → Coarse : coalesce the eight fine volumetric distribution functions**
- **Coarse → Fine : explode the coarse volumetric distribution function**
- **No rescaling of distribution functions**
- **No time-interpolation**

Chen, H. & al. 2005, *“Grid refinement in Lattice Boltzmann methods based on volumetric formulation*”, Physica A, 362 (1), 2006

# Immersed boundary model for complex geometry meshing



# Boundary condition on complex geometry (volumetric fomulation)



*- Chen, H. & al., Int. J. Modern Phys. C, 1997*
*- WO Patent 97/21195, Chen, Hill, Hoch, Molvig, Teixeira, Traub, 1997*

- **Outward distribution function flux for surface element *i***

$$\Gamma_i^{\alpha,out}(t) = \sum_{\tilde{x}_k=\Diamond} V_i^\alpha(\tilde{x}_k)\, g_\alpha(\tilde{x}_k, t)$$

- **No-slip boundary condition**

$$\Gamma_i^{\alpha,in}(t) = \Gamma_i^{-\alpha,out}(t)$$

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

$$\Gamma_i^{\alpha,in}(t) = -\Gamma_i^{-\alpha,out}(t) - \frac{1}{2\theta} C'_f u_t^i V_i^\alpha (\vec{c}_\alpha \cdot \vec{n}_i)\left(g_\alpha^{eq,i}(t) - g_{-\alpha}^{eq,i}(t)\right) + \dots$$

Friction force : $F_t^i(t) = -C'_f \rho u_t^{i^2} / 2$

| | |
|---|---|
| $u_t^i$ | tangential velocity in the first cell above the surface element *i* |
| $C'_f$ | local friction coefficient |

# Turbulence modeling in PowerFLOW

- **Standard approach :** $\tau \rightarrow \tau_{mol} + \tau_{turb}$
- **Calculation of** $\tau_{turb}$ **using a** $k-\varepsilon$ **model :**

$$\begin{cases} \rho \dfrac{\partial k}{\partial t} + \rho \bar{u}_i \dfrac{\partial k}{\partial x_i} = \dfrac{\partial}{\partial x_i}\left[\left(\dfrac{\mu}{\sigma_k} + \dfrac{\mu_T}{\sigma_{kT}}\right)\dfrac{\partial k}{\partial x_i}\right] + \tau_{ij}^r S_{ij} - \rho\varepsilon \\ \rho \dfrac{\partial \varepsilon}{\partial t} + \rho \bar{u}_i \dfrac{\partial \varepsilon}{\partial x_i} = \dfrac{\partial}{\partial x_i}\left[\left(\dfrac{\mu}{\sigma_\varepsilon} + \dfrac{\mu_T}{\sigma_{\varepsilon T}}\right)\dfrac{\partial \varepsilon}{\partial x_i}\right] + C_{\varepsilon 1}\dfrac{\varepsilon}{k}\tau_{ij}^r S_{ij} - \left[C_{\varepsilon 2} + C_\mu \dfrac{\tilde{\eta}^3\left(1-\tilde{\eta}/\eta_0\right)}{1+\beta\tilde{\eta}^3}\right]\rho\dfrac{\varepsilon^2}{k} \end{cases}$$

$$\left(\tau_{ij}^r = \overline{\rho u_i' u_j'} = 2\mu_T S_{ij} - \frac{2}{3}\rho k \delta_{ij}\right)$$

$$C_\mu = 0.085, \quad C_{\varepsilon 1} = 1.42, \quad C_{\varepsilon 2} = 1.68, \quad \sigma_k = \sigma_{kT} = \sigma_\varepsilon = \sigma_{\varepsilon T} = 0.719, \quad \eta_0 = 4.38, \quad \beta = 0.012$$

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

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

- **« Swirl modification » :** $\nu_T = C_\mu \dfrac{k^2}{\varepsilon}\dfrac{1}{1+\tilde{\eta}}$

# 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 ceilling values of $k$ and $\varepsilon$ to insure realizability of the turbulence quantities (for numerical stability)
- Near the wall : empirical boundary condition

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

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

*Pervaiz, M.M. & Teixeira, C.M., « Two equation turbulence modeling with the lattice Boltzmann method », 2nd Int. Symposium on Comput. Tech. For Fluid/Thermal/Chemical Systems with Industrial Applications. ASME PVP Division Conference, August 1-5 1999, Boston, MA.*

# 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

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

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

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

(adverse pressure gradient effect)

**3.** Definition of a local friction coefficient and friction force

$$C'_f = \frac{\rho u_*^2}{\rho u_t^2 / 2} \qquad F_i = -C'_f \rho \frac{u_t^2}{2}$$

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

$$\Gamma_i^{\alpha,in}(t) = f\left(C'_f u_t\right)$$

# Numerical stability management

- **« Base viscosity » approach**
  - Imposed minimum value of the non-dimensional relaxation time

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

*Normalized (dimensionless)* *Physical units*

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

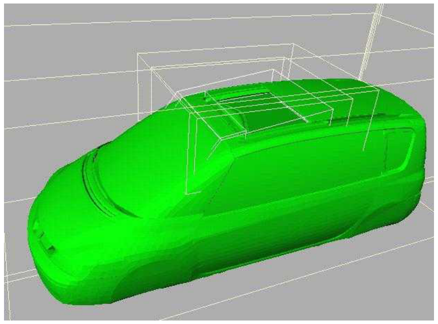
- **In high turbulent viscosity region**

$$\nu_{eff} \approx \nu_T > \nu_{base}$$

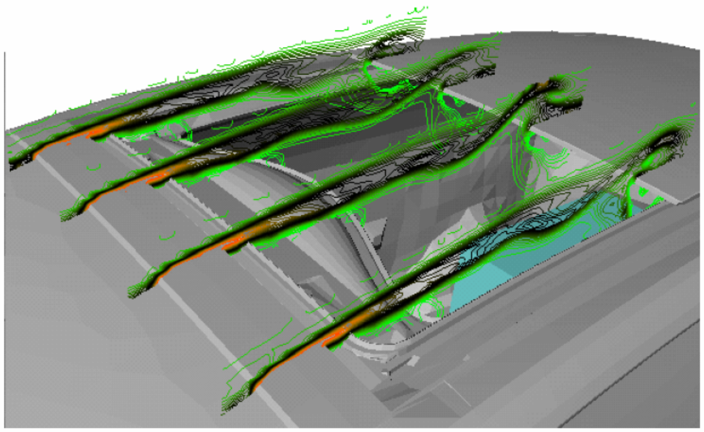
- **But in low turbulent viscosity region (near wall separation for example)**

$\nu + \nu_T < \nu_{base} \Rightarrow \nu_{eff} = \nu_{base} \Rightarrow$ unphysical high level of viscosity

# Numerical stability management

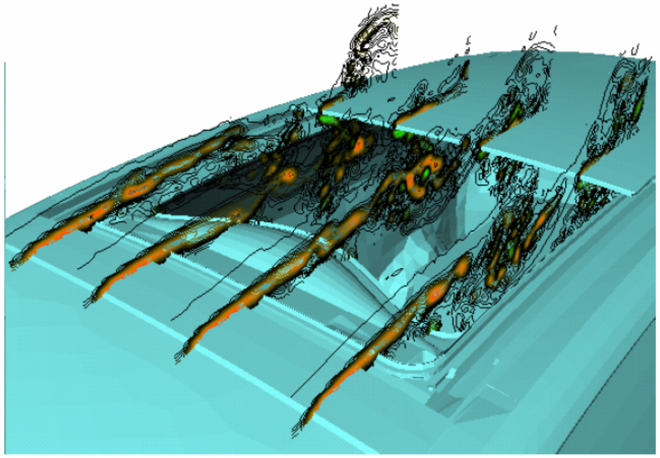


Sunroof buffeting simulation
*(D. Ricot, ECL, 2002)*



Standard base viscosity

$\nu_{eff} = \nu_{base} >> \nu + \nu_T$ near flow separation



“Manually” reduced base viscosity

$\nu_{eff} = \nu + \nu_T > \nu_{base}$

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- **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
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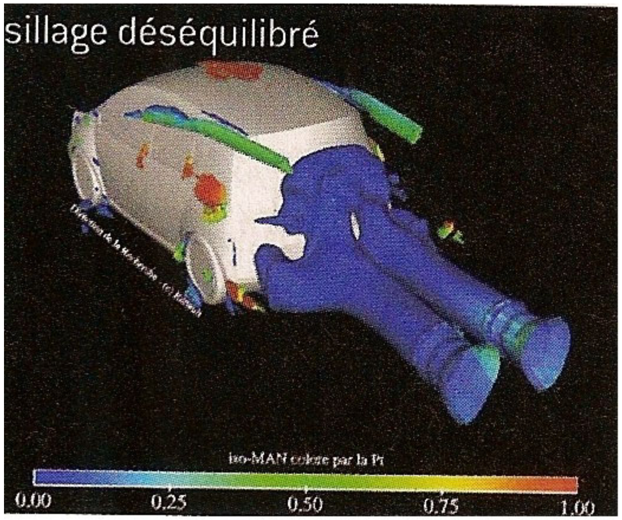
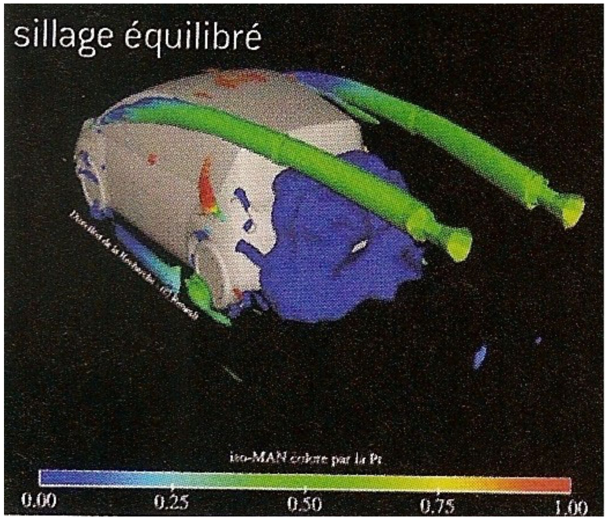
# Aerodynamic drag simulation

- **Objectives**
  - Drag and lift coefficient calculation → design choice to minimize $CO_2$ emission
  - Shape and detail optimizations



**"3D" wake (strong longitudinal vortices)**
**→ High drag**

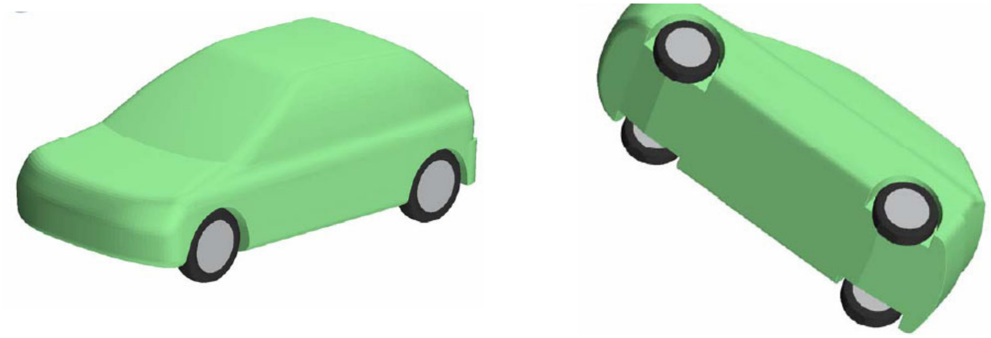


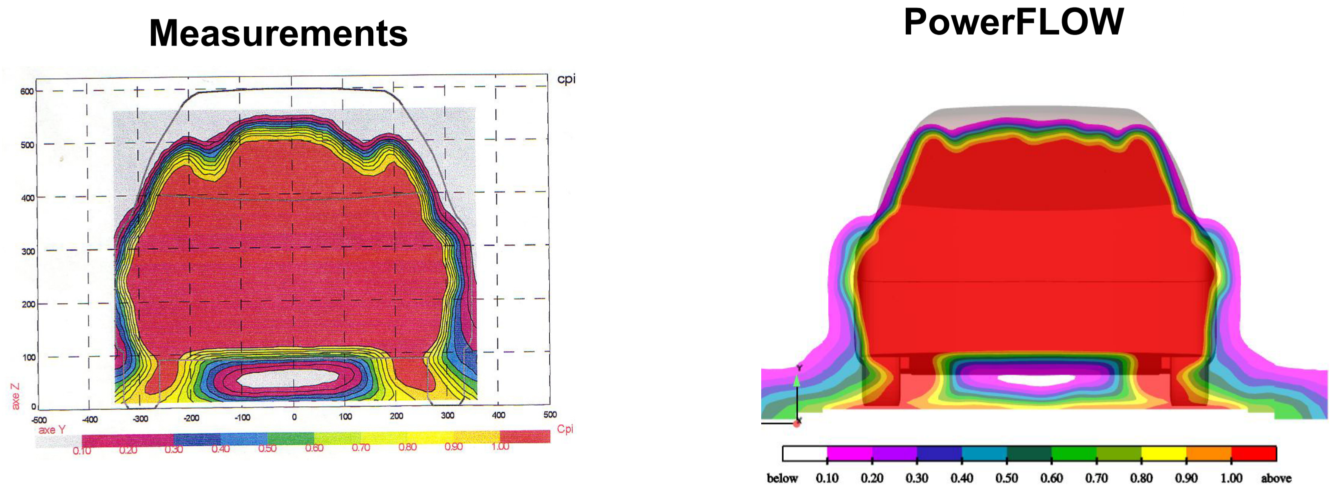
**"2D" wake**
**→ Low drag**

*S. Parpais, Renault R&D mag., 2003*

# Validation of aerodynamic drag simulation

- **First validation on simplified car**
  - No underhood
  - Flat underbody



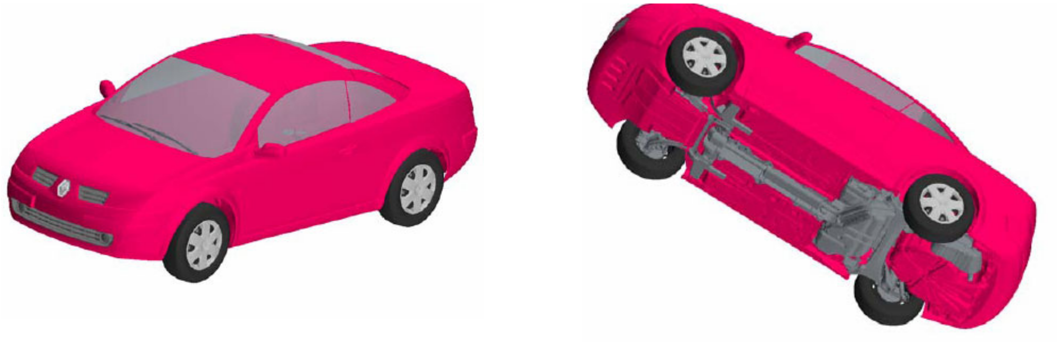


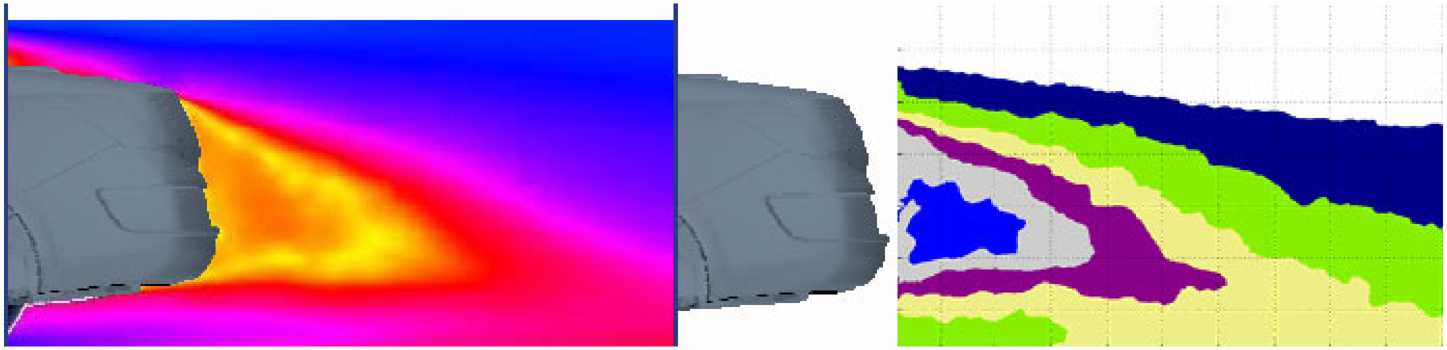
**Measurements** **PowerFLOW**

**<u>Total pressure loss 10 mm downstream the simplified car</u>**

# Validation of aerodynamic drag simulation

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





**PowerFLOW**

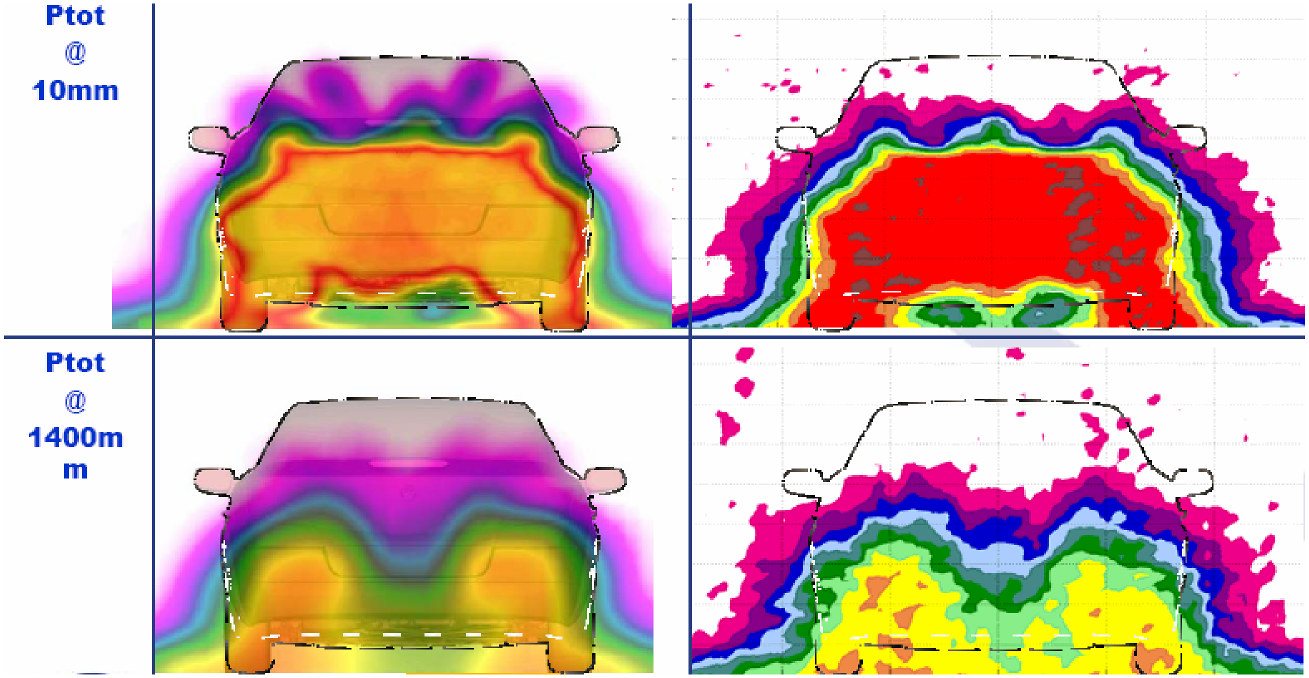
**Measurements**

Normalized (Ux / U0) longitudinal mean velocity in the symetry plane

# Validation of aerodynamic drag simulation

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

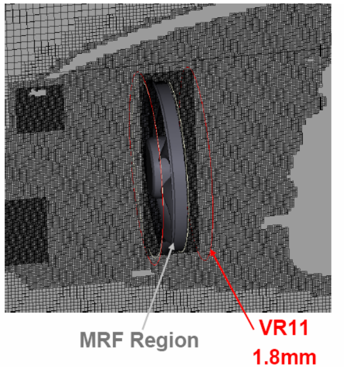
**PowerFLOW** **Measurements**



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

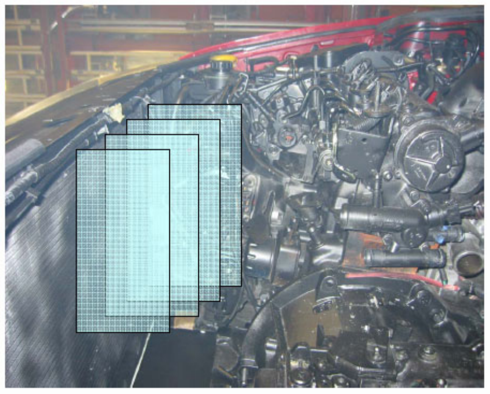
# Underhood flow

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

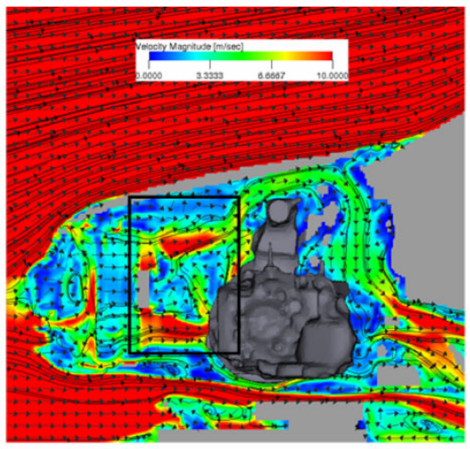


- **Experimental validation based on PIV measurements**

*O. Bailly et al., SIA, Lyon 2005*

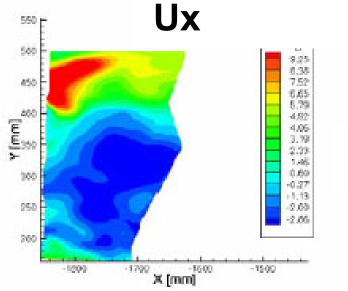


**PIV measurements**

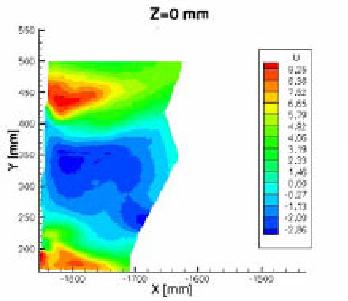


**PowerFLOW**

**Ux**



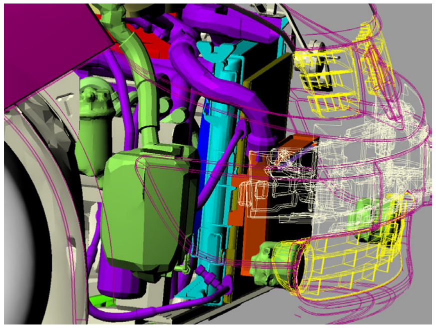
**Measurements**

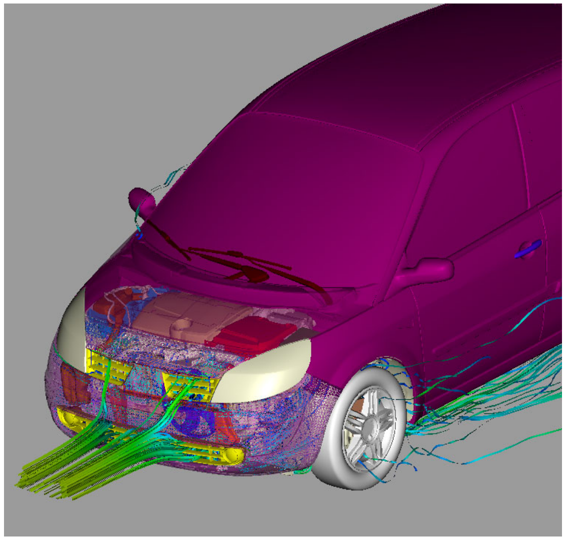


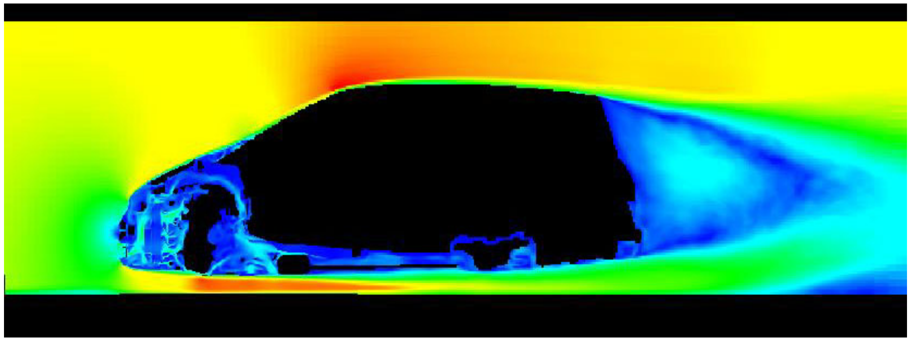
**PowerFLOW**

# Validation of aerodynamic drag simulation with underhood

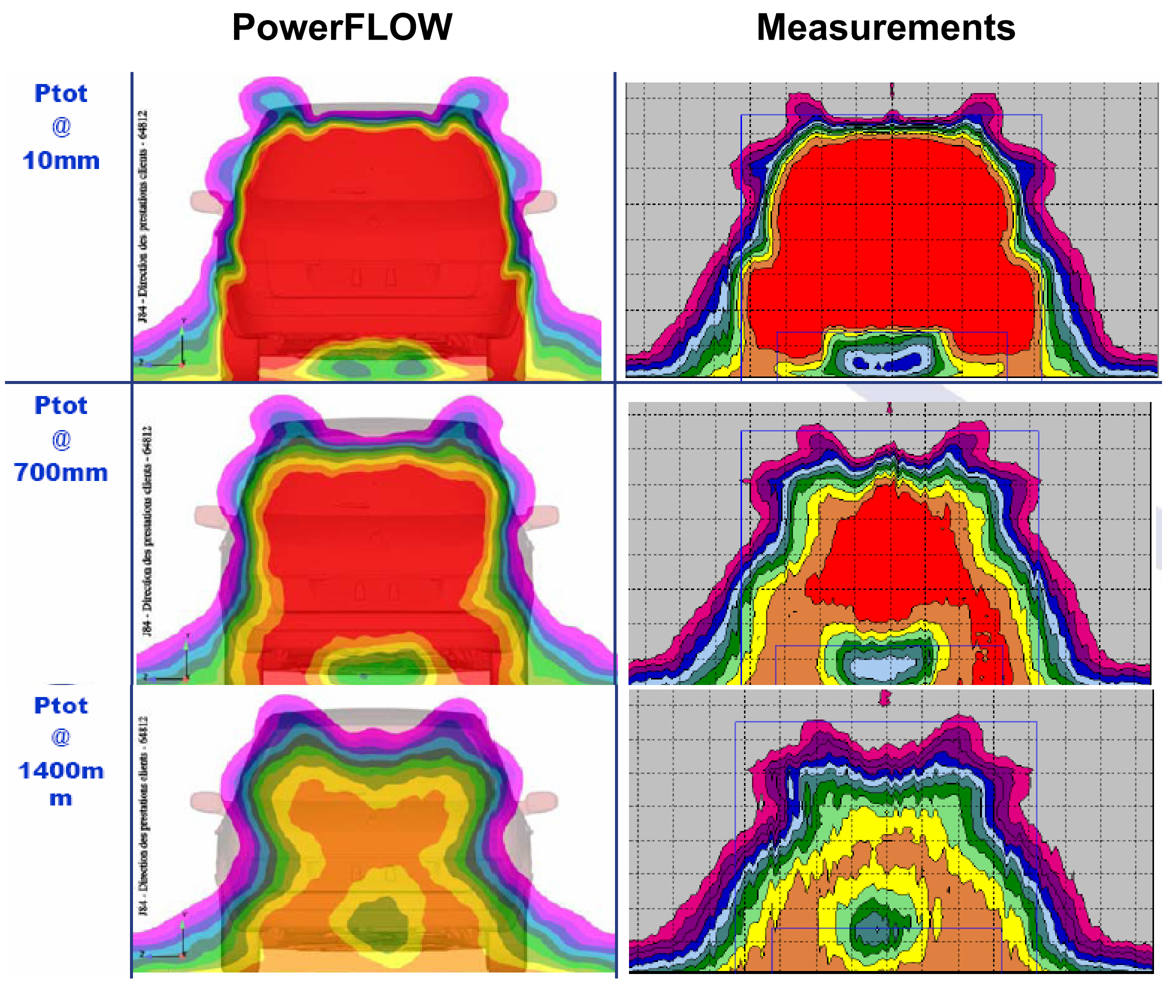
- **Validation on Scenic**
  - Fully detailed underbody
  - Underhood flow







# Validation of aerodynamic drag simulation with underhood flow



**PowerFLOW**

**Measurements**

**Ptot @ 10mm**

**Ptot @ 700mm**

**Ptot @ 1400mm**

**Total pressure loss in the Scenic wake**

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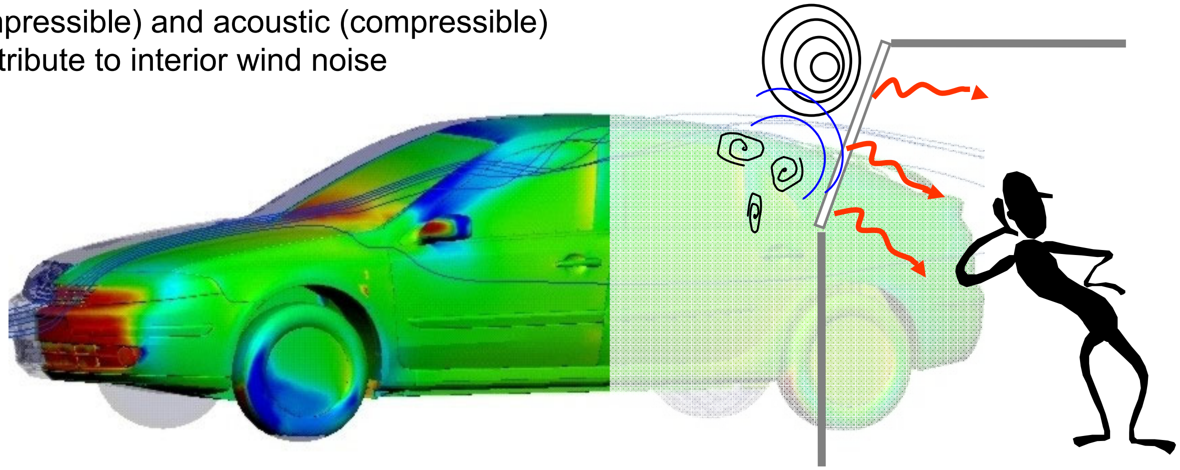
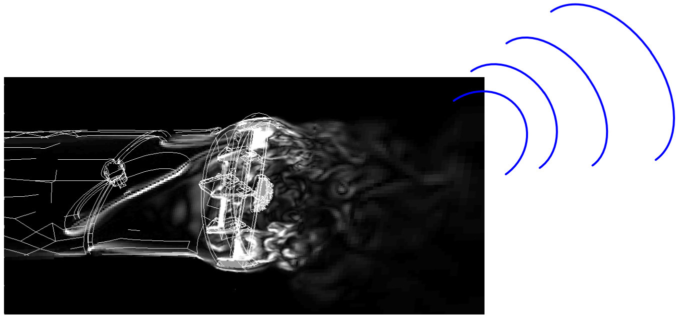
# Aeroacoustic simulations

- **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

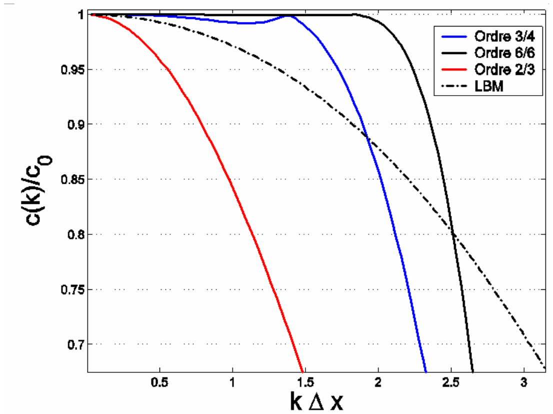


Lateral HVAC
outlet of Twingo

# Acoustic propagation with LBM : theoretical study

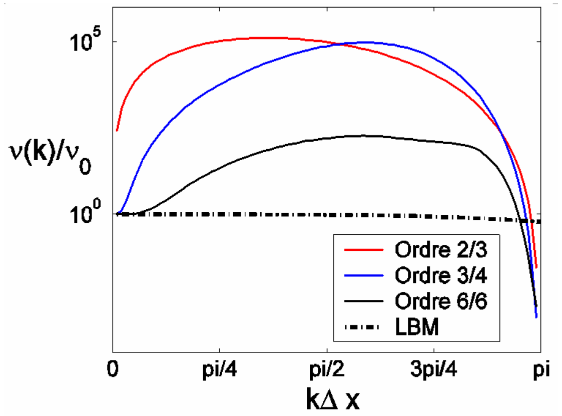
- **Von Neumann analysis of the LB models**
- **Comparison with optimized finite difference Navier-Stokes schemes (DRP : Dispersion Preserving Relation)**
  - Lower numerical dissipation than all aeroacoustic-optimized schemes
  - Lower dispersion error than FD of order 2 in space and 3 in time (Runge-Kutta)
  - Higher dispersion error than FD of order 3 in space and 4 in time (Runge-Kutta)
  - … but much lower computational effort in term of number of floating point operations + compact scheme

Dispersion error



*Number of points per wavelength*

Dissipation error

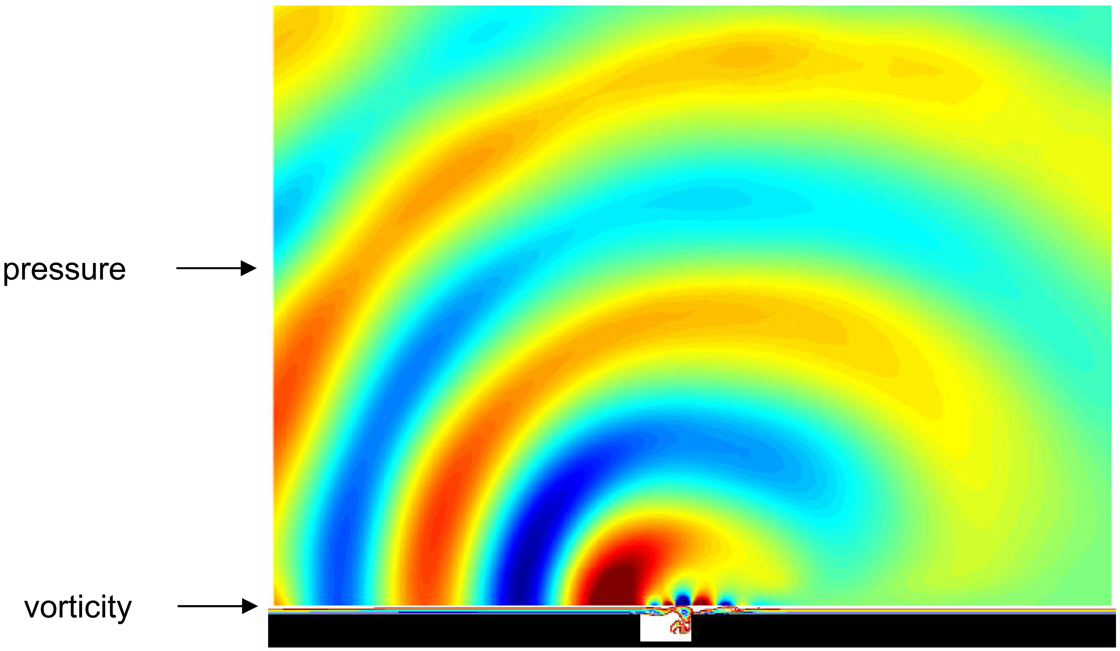


*Number of points per wavelength*

*(S. Marié et al., J. Comput. Phys., 2008)*

# Example of direct noise calculation with LBM

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



**Direct noise computation of a flow over cavity**

*Ricot D., Maillard V., Bailly C.,*
*AIAA paper 2002-2532*

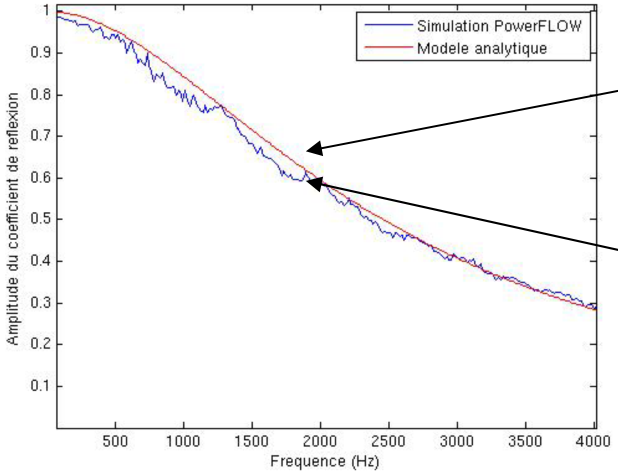
$$Mach = 0.25$$
$$\mathrm{Re}_L = 8 \cdot 10^3$$
$$St = fL/U_0 = 0.89$$

(Rossiter mode 2)

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

# Acoustic impedance of outlets, without mean flow

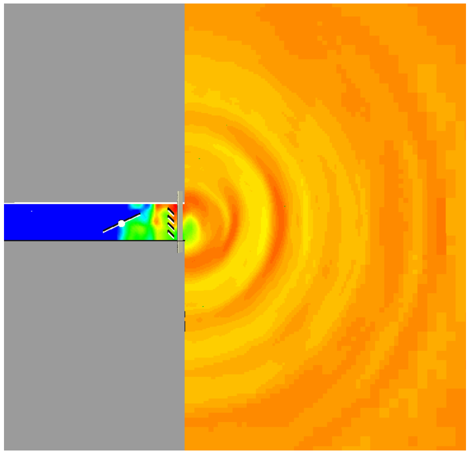
Acoustic reflection coefficient of a **circular baffled open termination**



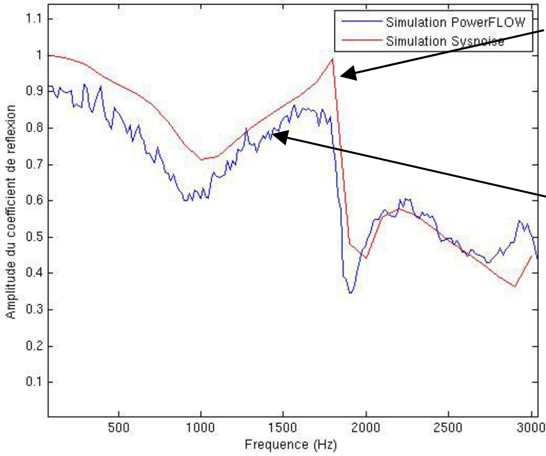
Analytical expression

LBM simulation

LBM simulation



Acoustic reflection coefficient of a HVAC duct outlet

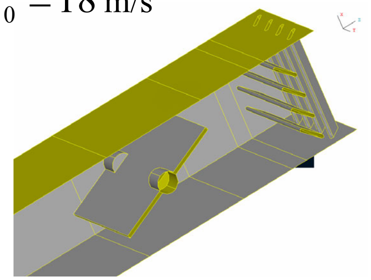


Sysnoise (BEM) simulation

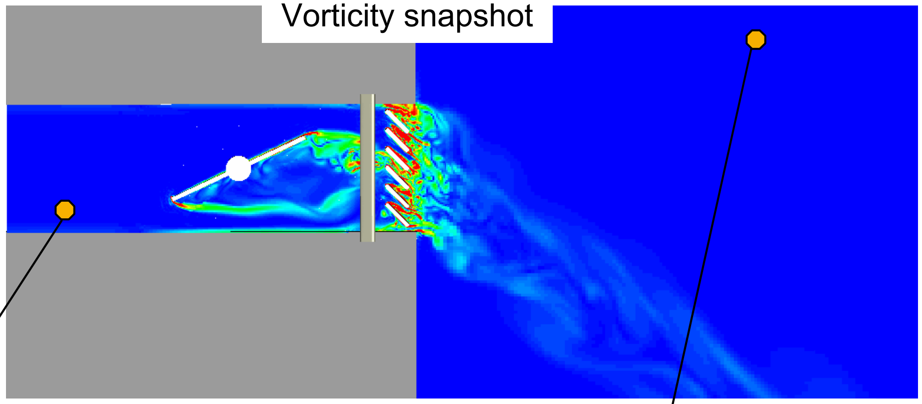
LBM simulation

# Noise generated by HVAC vents

$U_0 = 18 \text{ m/s}$

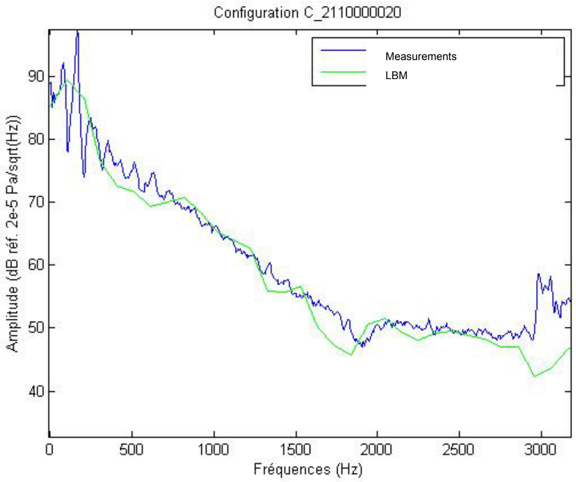


Vorticity snapshot

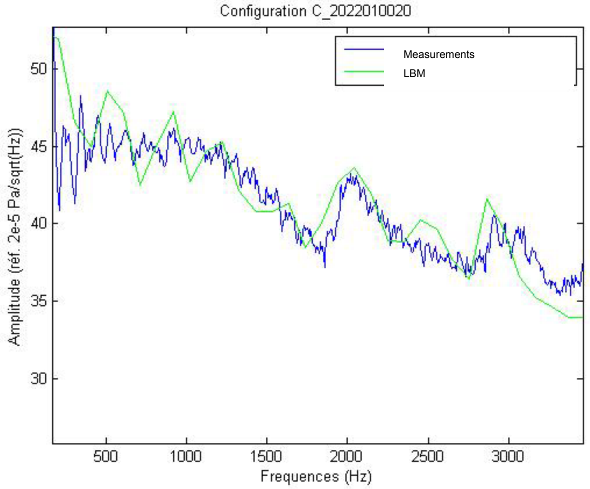


*(J.-L. Adam et al., Acoustics’08, Paris)*

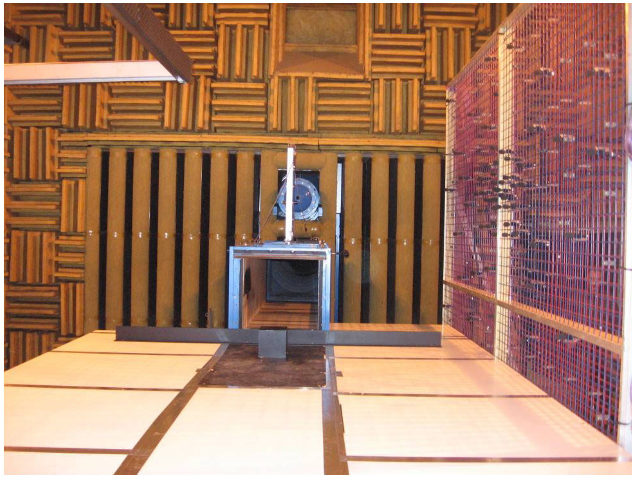
Upstream acoustic pressure



Downstream acoustic pressure



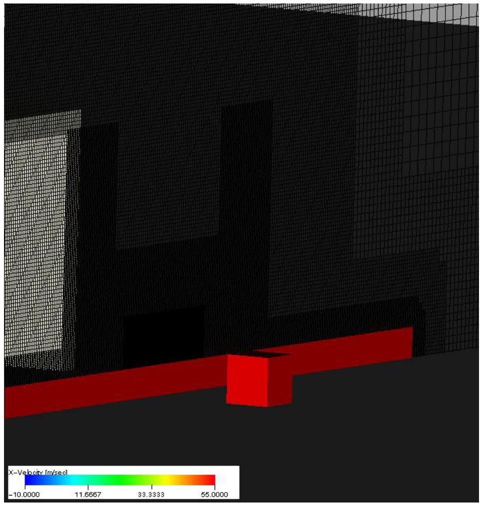
# Fence-cube configuration (MIMOSA Project)

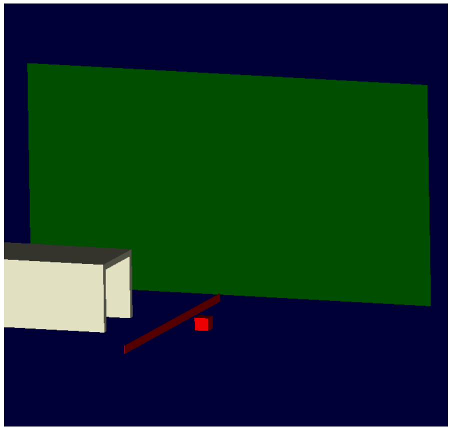


Measurements in the aeroacoustic wind tunnel of LMFA using a microphone array

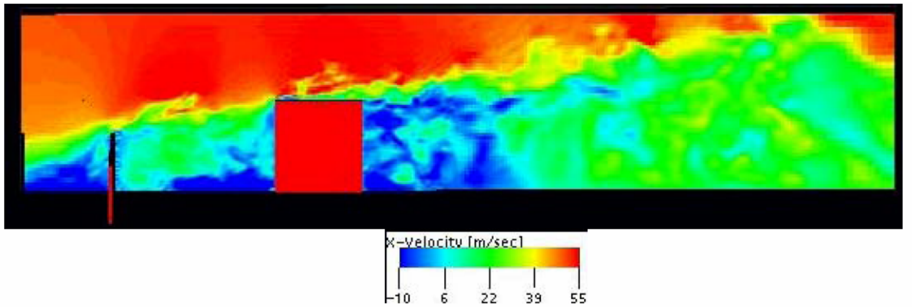
- $U_0$= 50 m/s
- dx_mini = 1 mm
- 50 millions of cells

*(H. Illy et al., DLES 2008)*





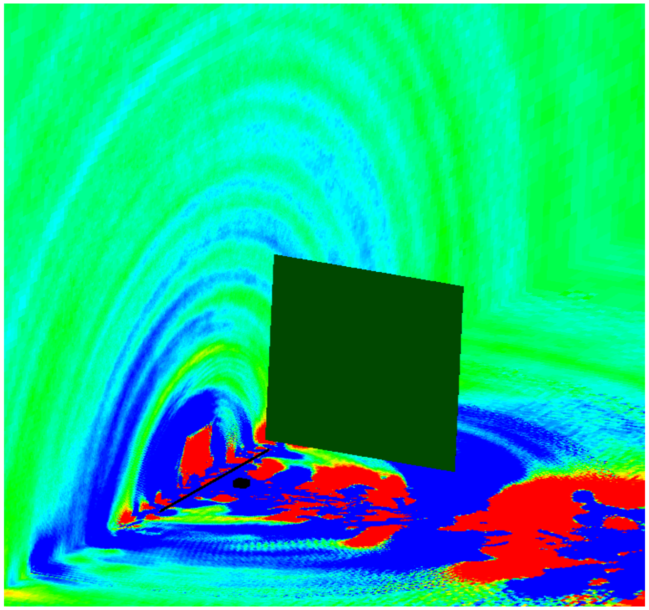
PowerFLOW

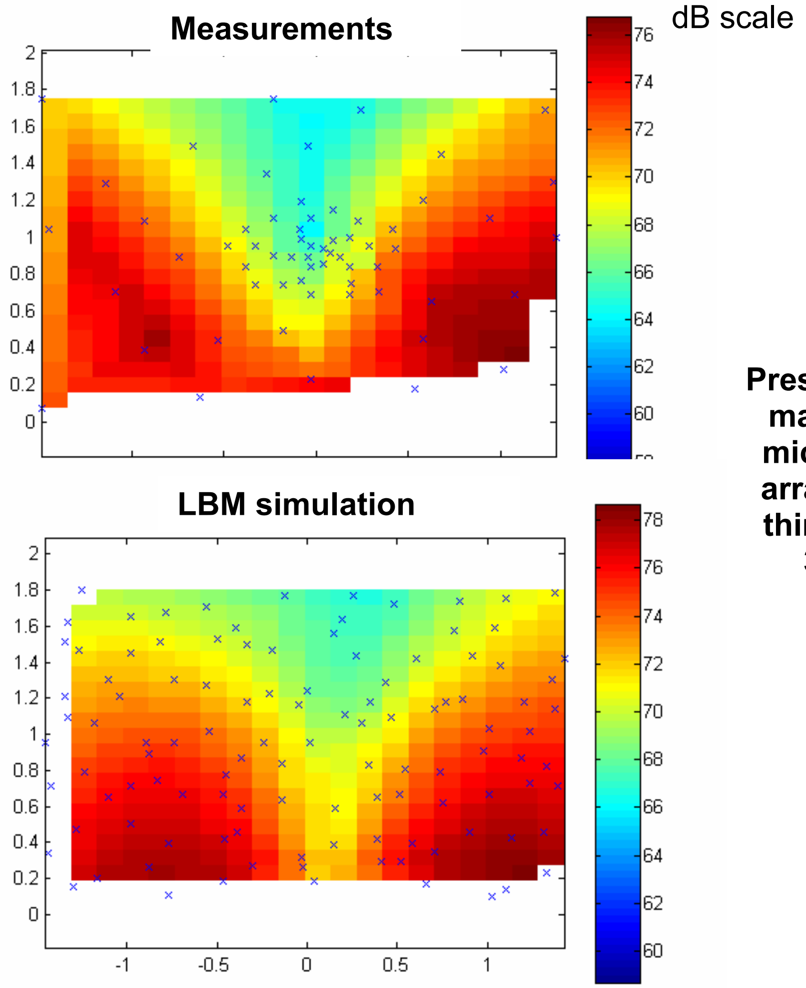


Snapshot of the Ux velocity in the symmetry plane

# 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**

# 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**