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

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with contributions of :
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Simon Marié, *Renault & Paris 6*
Pierre Sagaut, *Paris 6*

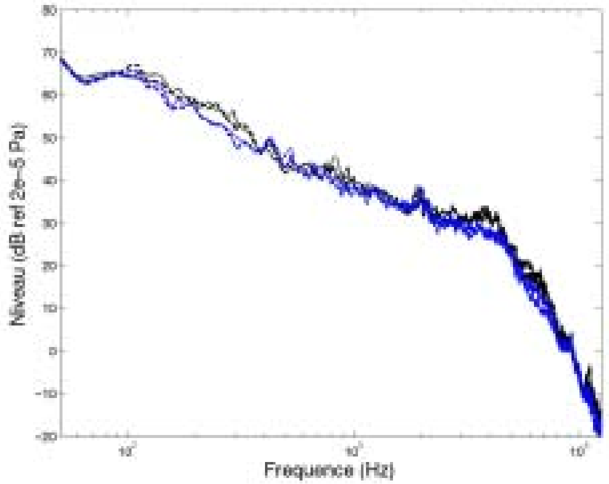
Outline

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

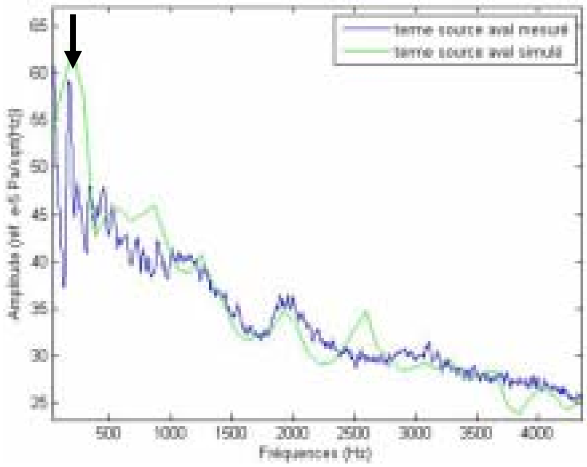
Aeroacoustic problems

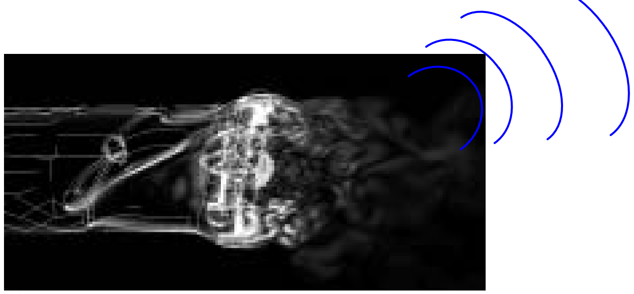
- **Interior noise aeroacoustics**
  - Broadband noise with, sometimes, unwanted frequency peaks
  - Relevant frequency range : all the audible spectrum (20 Hz → 10 kHz)

Example of interior aeroacoutic noise spectra



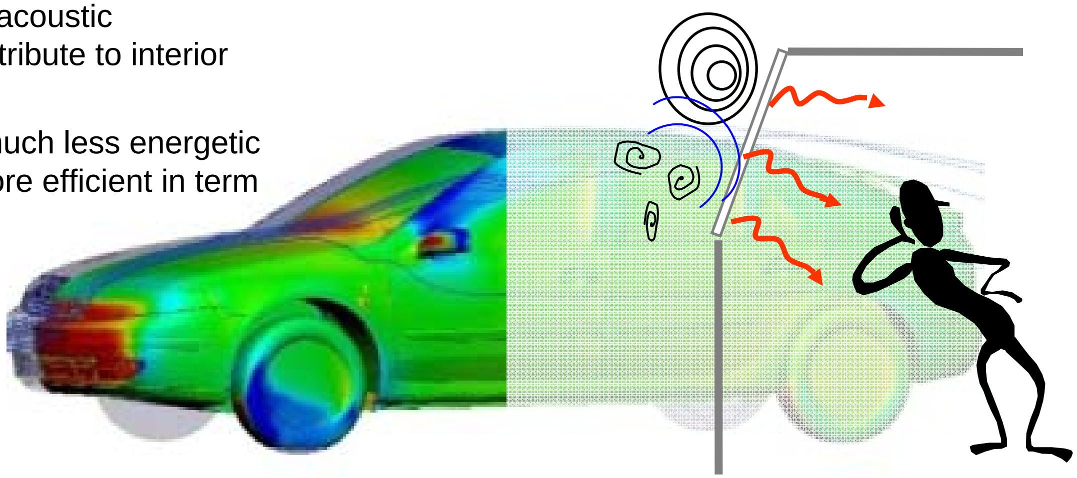
Noise generated by HVAC outlet vent



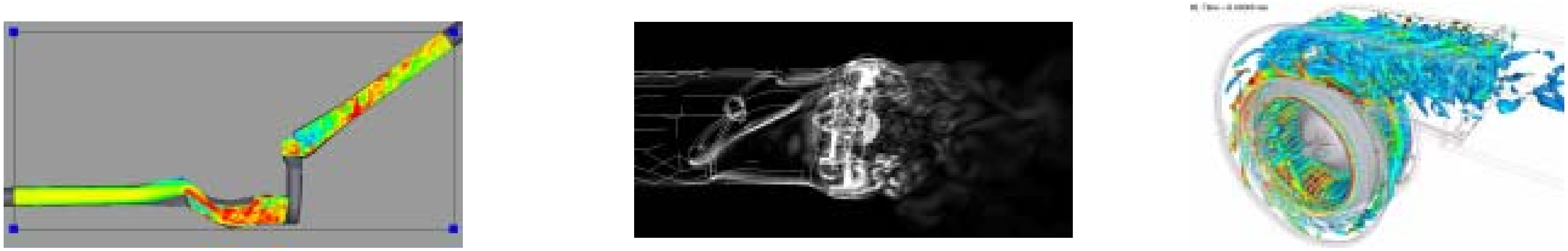


Automotive aeroacoustics

- **“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



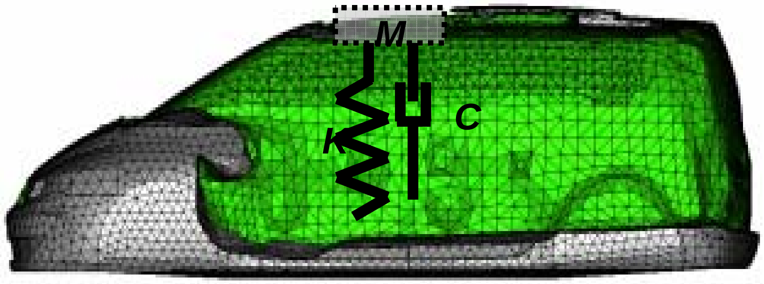
- **“Internal” aeroacoustics**
  - Source and propagation in ducts (HVAC, inlet and exhaust engine ducts)
  - Fan noise, aerodynamic noise generated by flow through ventilation outlets



Automotive aeroacoustics : cavity noise

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

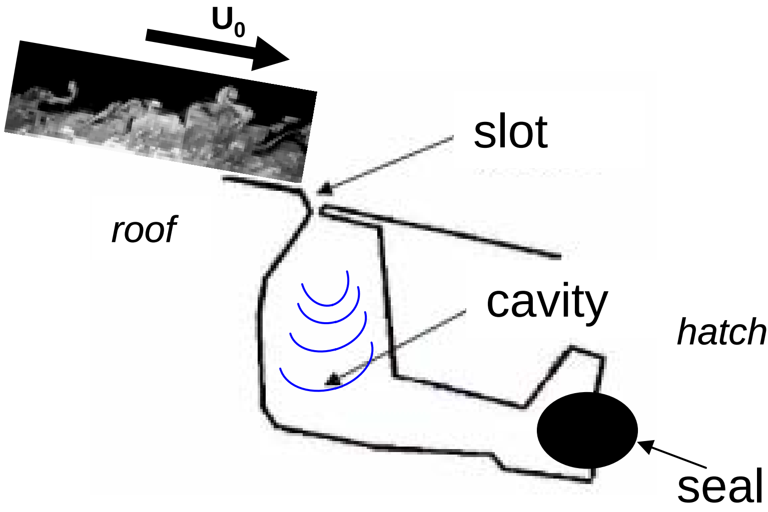
+



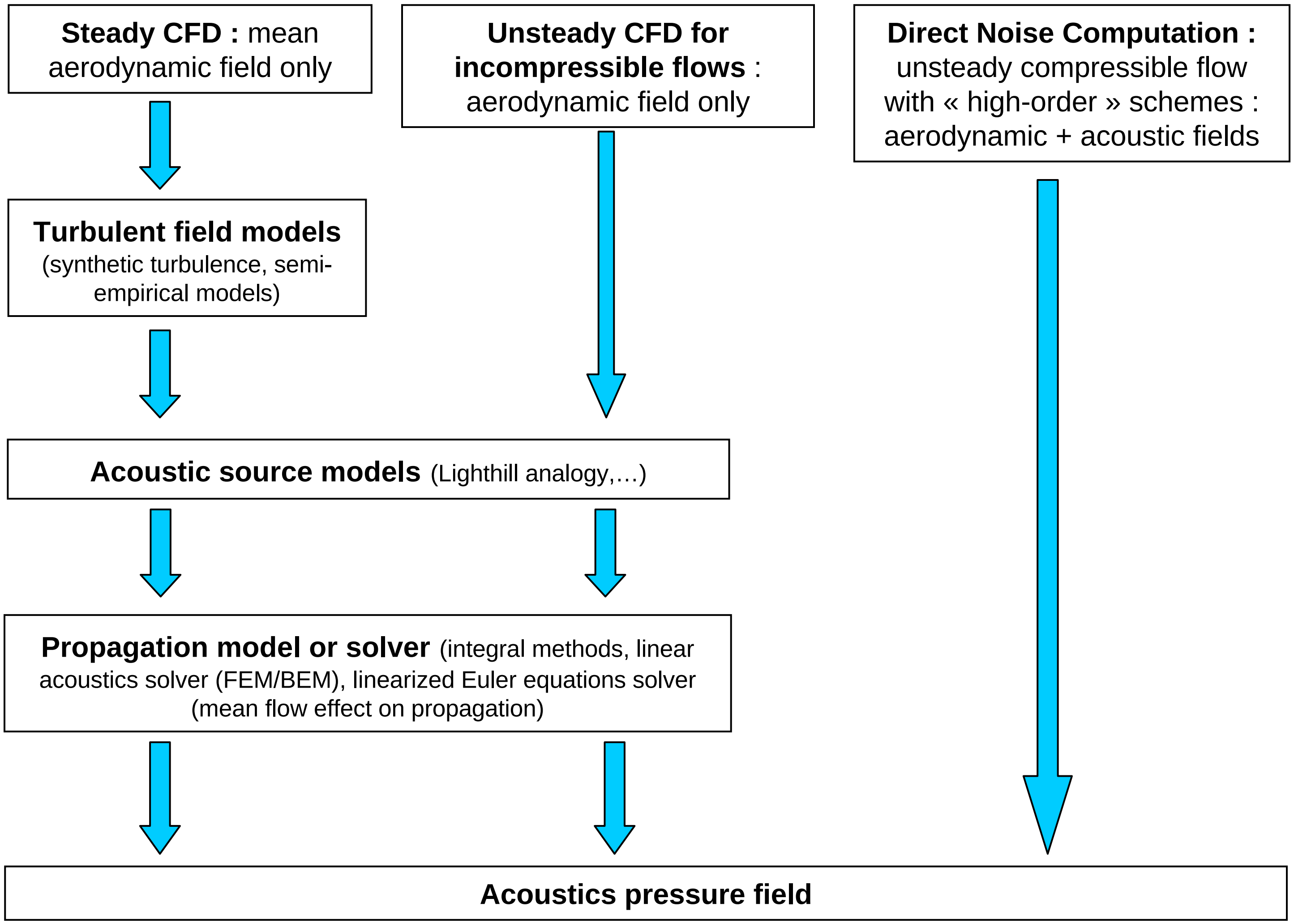
Helmholtz cavity resonance

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

Example : cavity between the hatchback and the roof



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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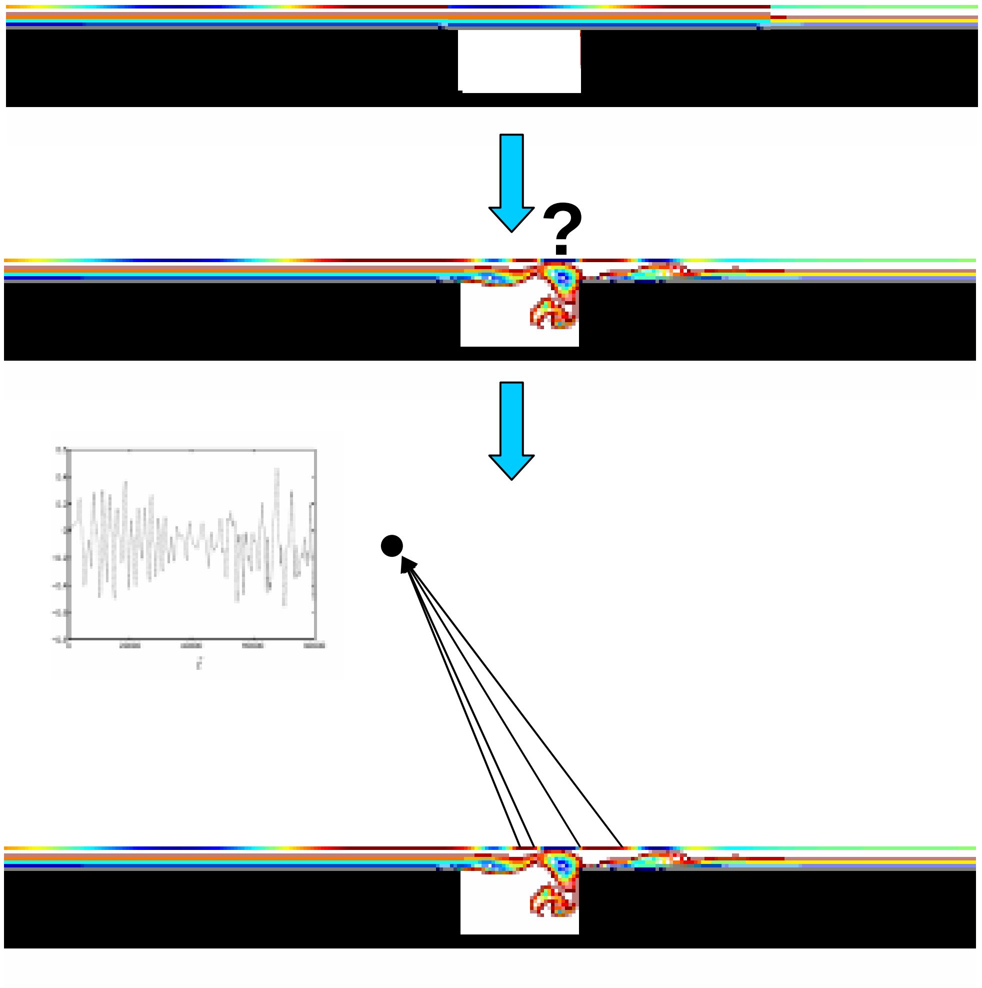

Acoustics pressure field

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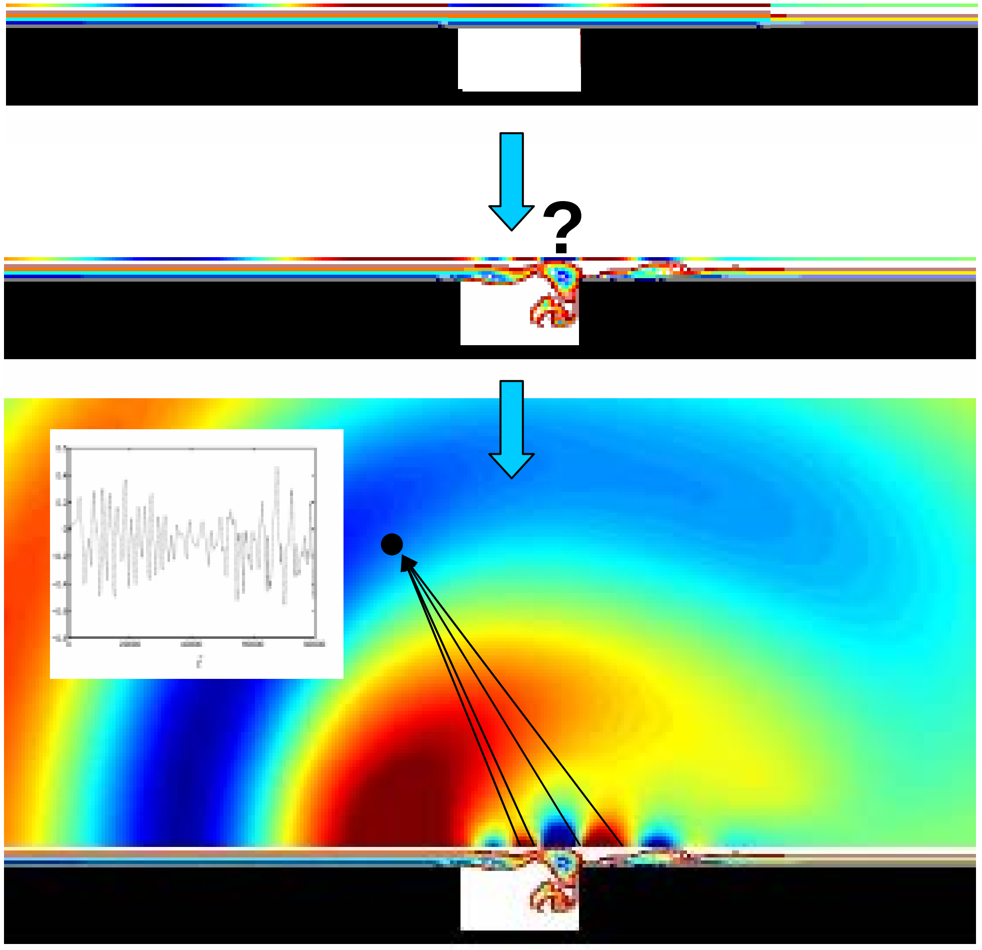

Computational AeroAcoustics : hybrid and direct approaches

Steady CFD : mean aerodynamic field only

Very difficult for real (complex) flows (OK for homogeneous turbulence, axi-symetric jets,...)

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)

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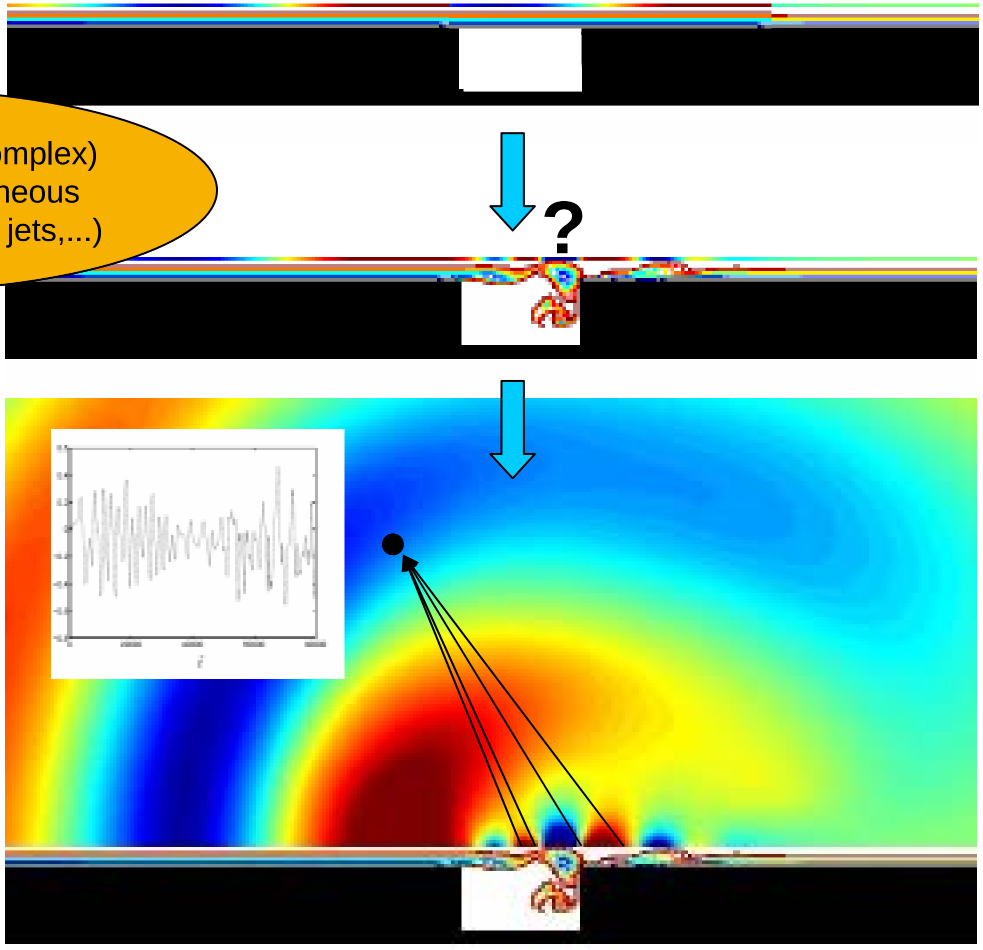

Computational AeroAcoustics : hybrid and direct approaches

Unsteady CFD for incompressible flows : aerodynamic field only

↓

Acoustic source models (Lighthill analogy,…)

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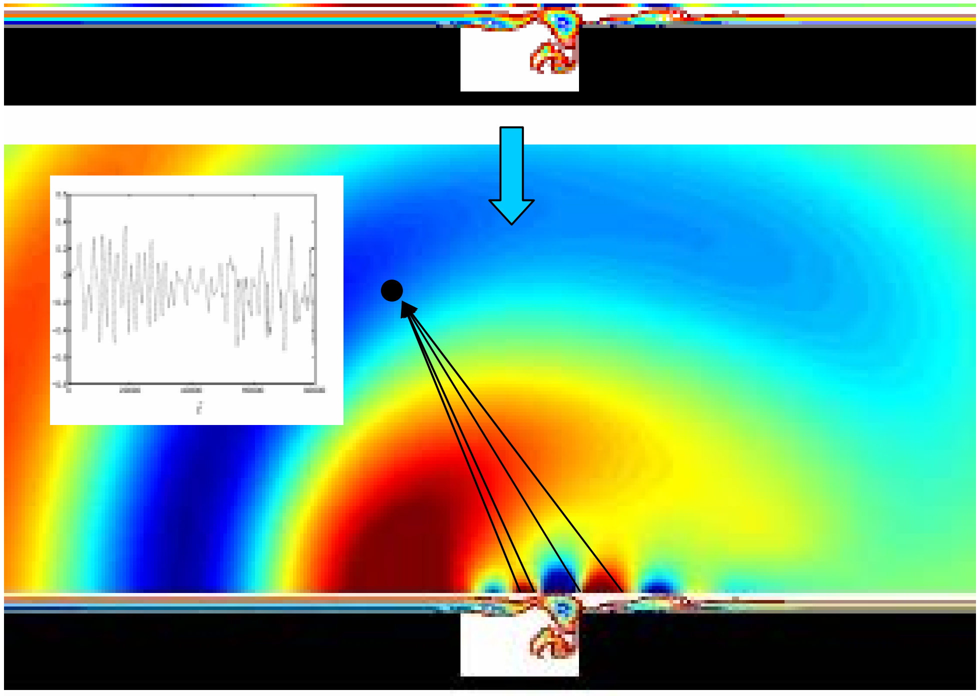
Propagation model or solver (integral methods, linear acoustics solver (FEM/BEM), linearized Euler equations solver (mean flow effect on propagation)

↓

Acoustics pressure field



Computational AeroAcoustics : hybrid and direct approaches

Unsteady CFD for incompressible flows : aerodynamic field only

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Acoustic source models (Lighthill analogy,…)

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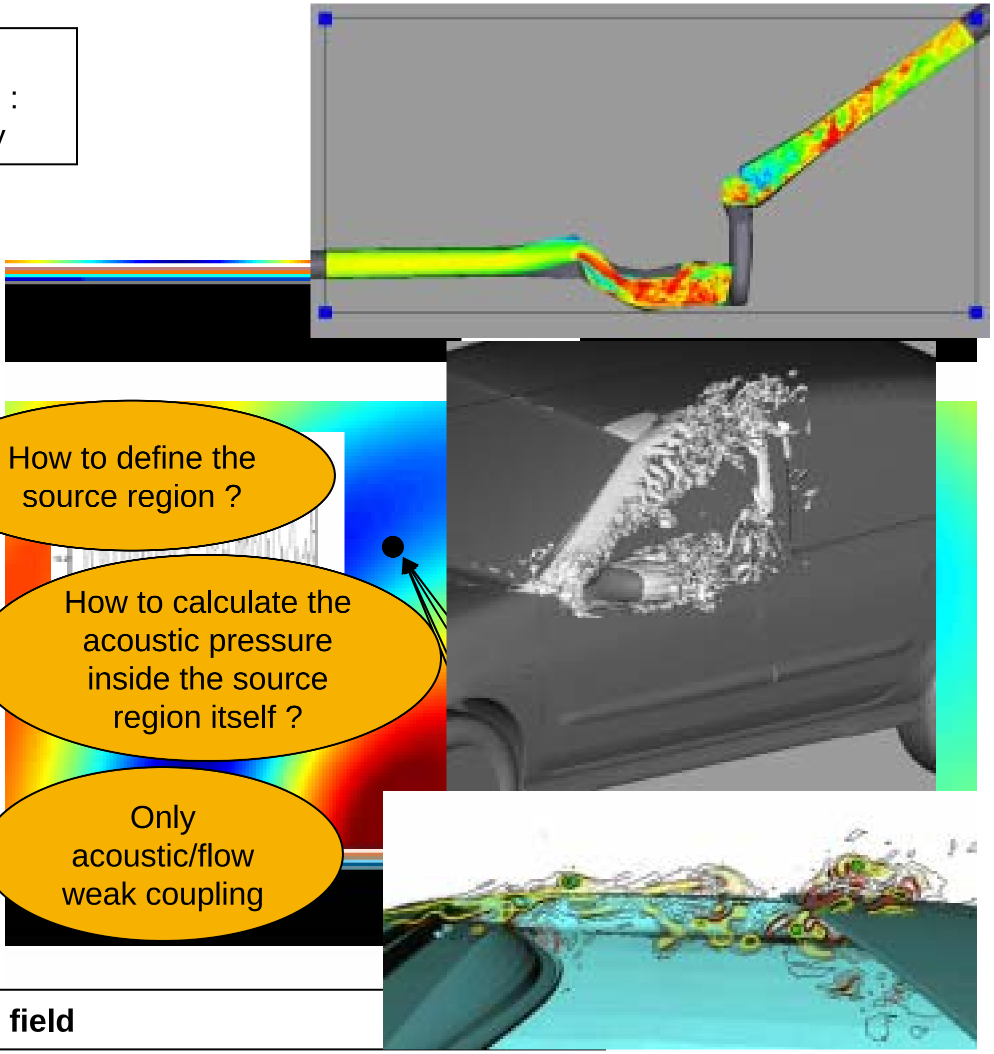
Acoustics pressure field



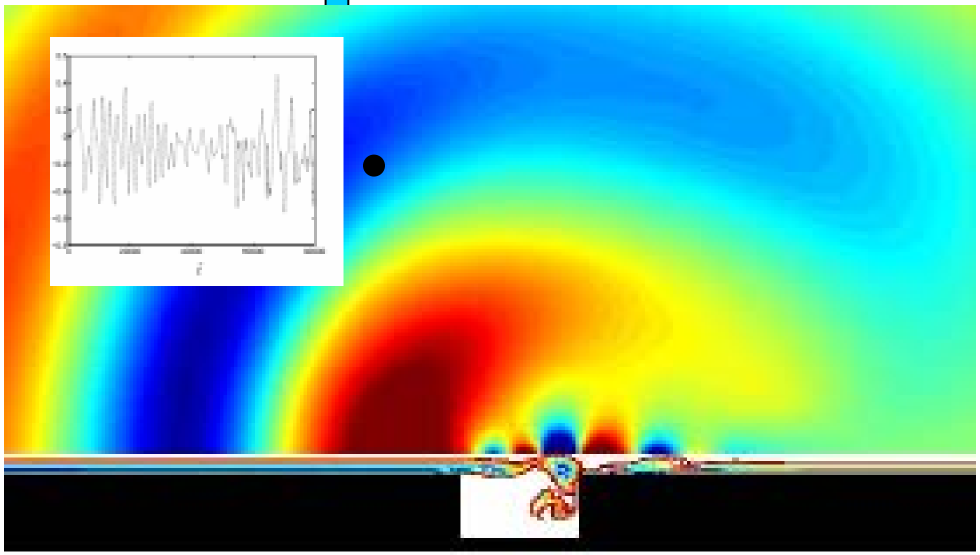
How to define the source region ?

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

Only acoustic/flow weak coupling

Computational AeroAcoustics : hybrid and direct approaches

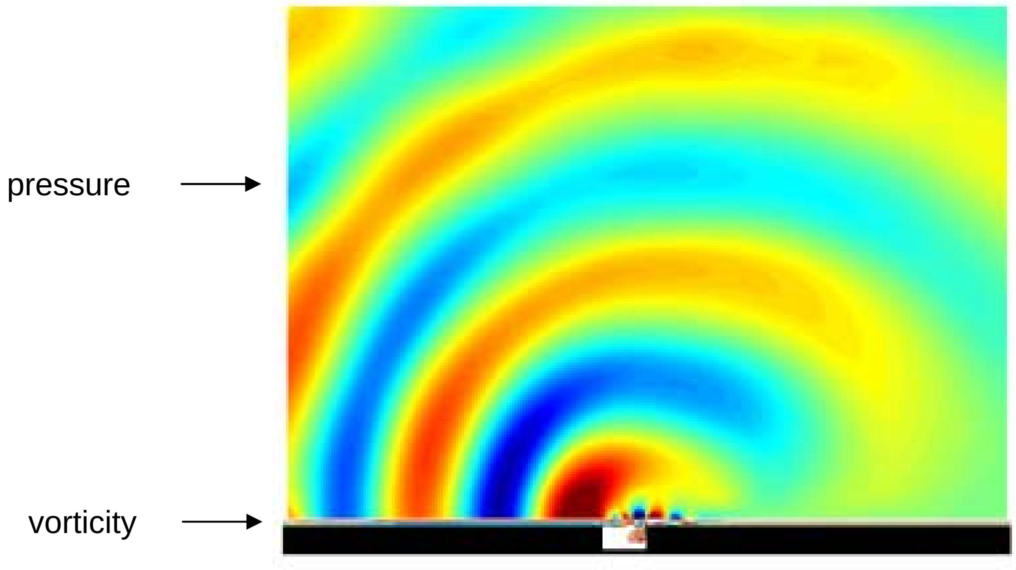
Direct Noise Computation :
unsteady compressible flow
with « high-order » schemes :
aerodynamic + acoustic fields



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



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)

Other examples :

→ A. Lafitte, F. Perot, Investigation of the Noise Generated by Cylinder Flows Using a Direct Lattice-Boltzmann Approach, 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference), 11 - 13 May 2009, Miami, Florida,AIAA 2009-3268

→ Wilde, A., Application of the Lattice-Boltzmann method in flow acoustics. In 4th SWING Aeroacoustic Workshop, Aachen (2004)

von Neumann analysis

Linearization of the equilibrium function around a uniform mean flow :

$$f_\alpha^{eq}\left(f_\alpha^{(0)} + f_\alpha^{'}\right) \qquad f_\alpha^{eq} = \rho\omega_\alpha\left(1 + 3\mathbf{u}.\mathbf{c}_\alpha + \frac{9(\mathbf{u}.\mathbf{c}_\alpha)^2}{2} - \frac{3|\mathbf{u}|^2}{2}\right)$$

Search for the plane wave solutions of the linearized equation : $f'_\alpha = \hat{A}_\alpha exp[i(\mathbf{k}.\mathbf{x} - \omega t)]$

Eigenvalue/eigenvector problem :

DVBE – BGK : $\frac{\partial f_\alpha}{\partial t} + c_{\alpha,i}\frac{\partial f_\alpha}{\partial x_i} = -\frac{1}{\tau}[f_\alpha - f_\alpha^{eq}]$ $\longrightarrow$ $i\omega\mathbf{f}' = \mathbf{M}^{\mathrm{DVBE}}\mathbf{f}'$

LBM – BGK : $g_\alpha(x+c,t+1) = g_\alpha(x,t) - \frac{1}{\tau_g}\left(g_\alpha(x,t) - g_\alpha^{eq}(x,t)\right)$ $\longrightarrow$ $e^{-i\omega}\mathbf{g}' = \mathbf{M}^{\mathrm{BGK}}\mathbf{g}'$

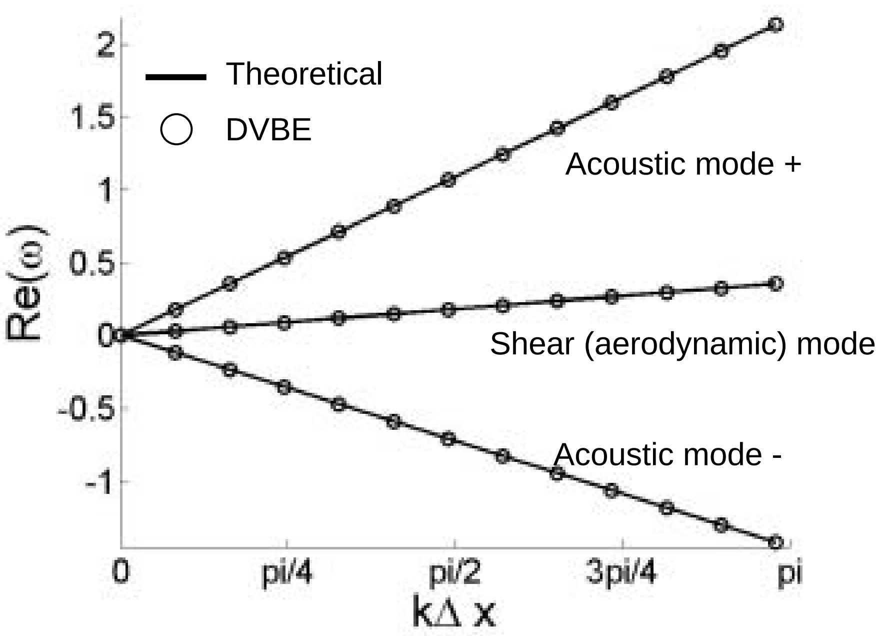
LBM – MRT : $\mathbf{g}(\mathbf{x}+\mathbf{c}, t+1) = \mathbf{g}(\mathbf{x}, t) - P^{-1}S[\mathbf{m}(\mathbf{x}, t) - \mathbf{m}^{eq}(\mathbf{x}, t)]$ $\longrightarrow$ $e^{-i\omega}\mathbf{g}' = \mathbf{M}^{\mathrm{MRT}}\mathbf{g}'$

Velocity model : D3Q19

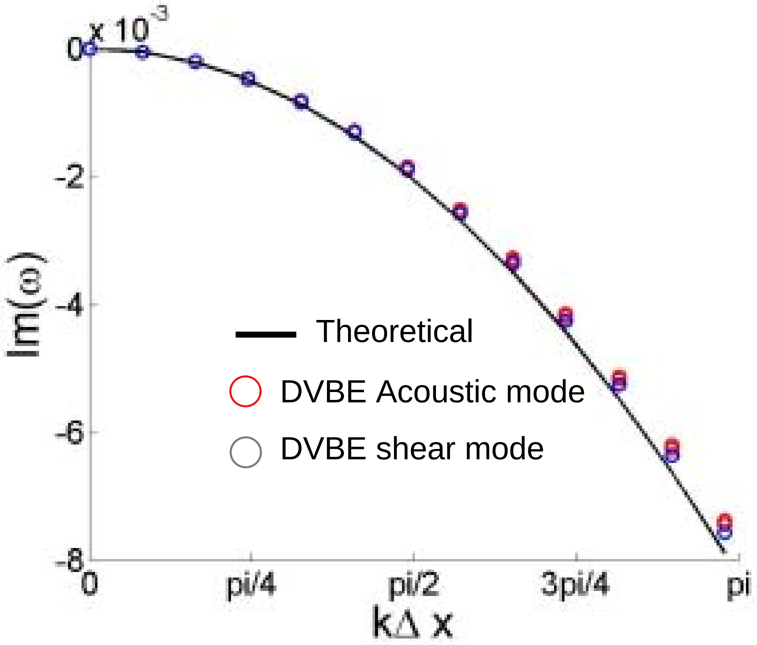
Discrete Velocity Boltzmann Equation

Ma = 0.2

Dispersion



Dissipation

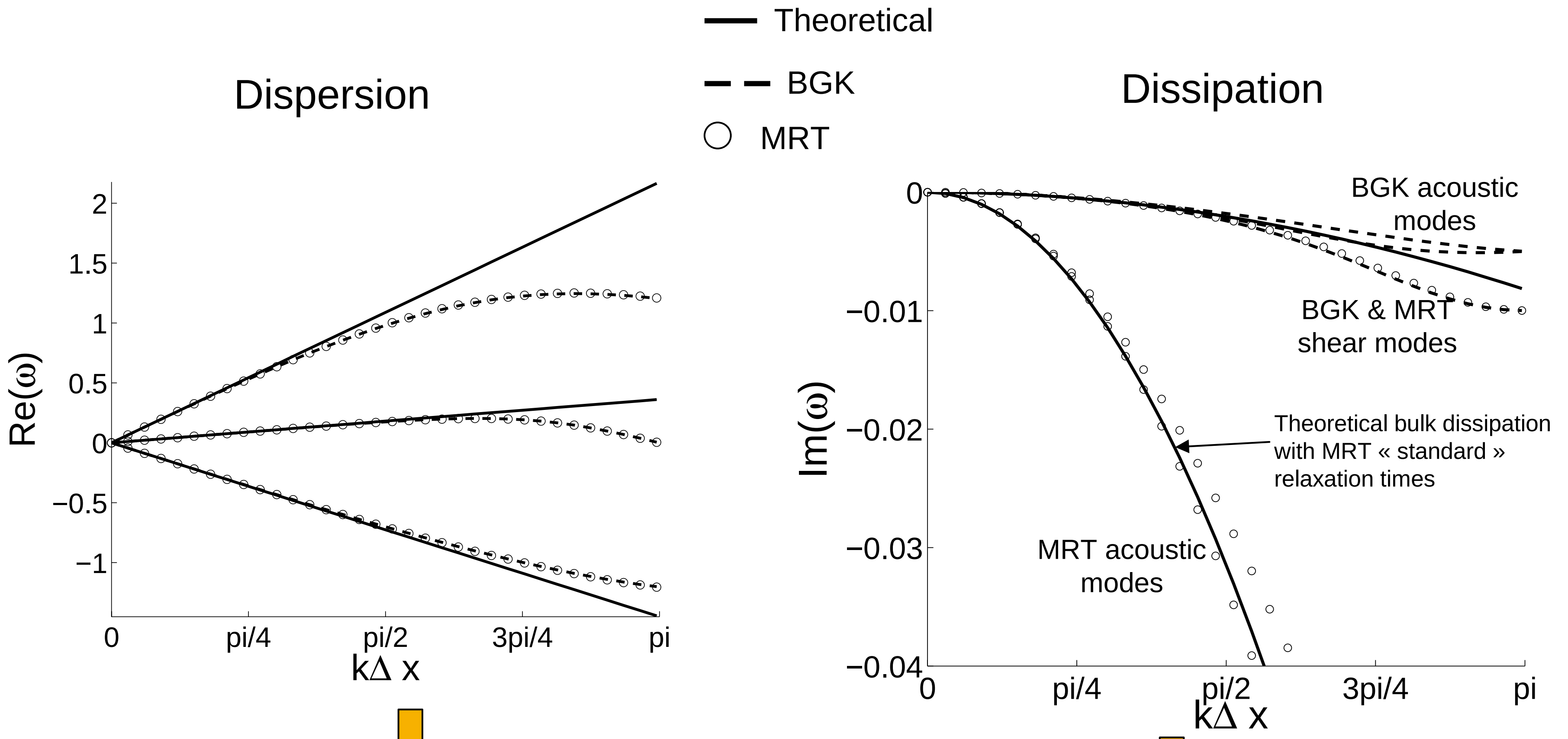


DVBE : strictly exact in term of dispersion

DVBE : small error in the dissipation due to the M^3 error term

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \boxed{-\tau\frac{\partial \rho u_i u_j u_k}{\partial x_k}}$$

LBM-BGK and LBM-MRT


Dispersion

Dissipation

BGK & MRT : same dispersion error

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

Von Neumann analysis applied to Navier-Stokes schemes

Linearized Navier-Stokes equations :

$$\frac{\partial \mathbf{U}'}{\partial t} + \frac{\partial}{\partial x_1}[\mathbf{E}'_\mathrm{e} - \mathbf{E}'_\mathrm{v}] + \frac{\partial}{\partial x_2}[\mathbf{F}'_\mathrm{e} - \mathbf{F}'_\mathrm{v}] + \frac{\partial}{\partial x_3}[\mathbf{G}'_\mathrm{e} - \mathbf{G}'_\mathrm{v}] = 0$$

Euler terms

viscous terms

$$\mathbf{U}' = \begin{pmatrix} \hat{\rho}' \\ \rho_0 \hat{u}' \\ \rho_0 \hat{v}' \\ \rho_0 \hat{w}' \\ \hat{p}' \end{pmatrix} exp[i(\mathbf{k}.\mathbf{x} - \omega t)]$$

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:

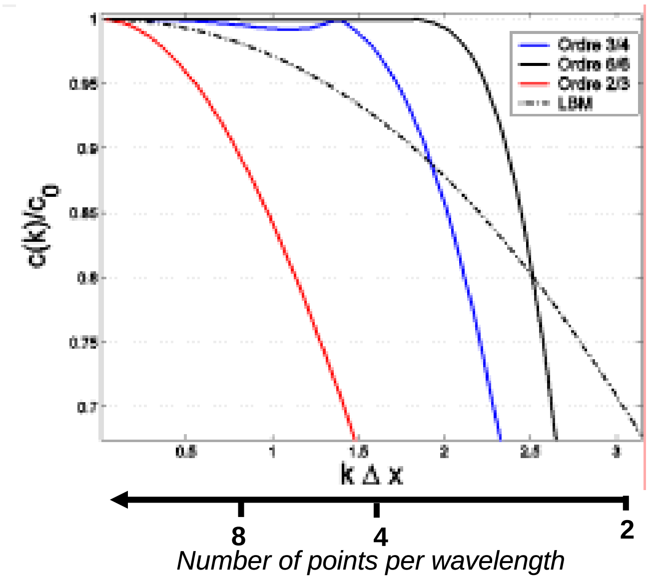
$$\mathbf{U}^{n+1} = \mathbf{U}^n + \sum_{j=1}^{p} \gamma_j \Delta t^j F^j(\mathbf{U}^n)$$

Eigenvalue/eigenvector problem:

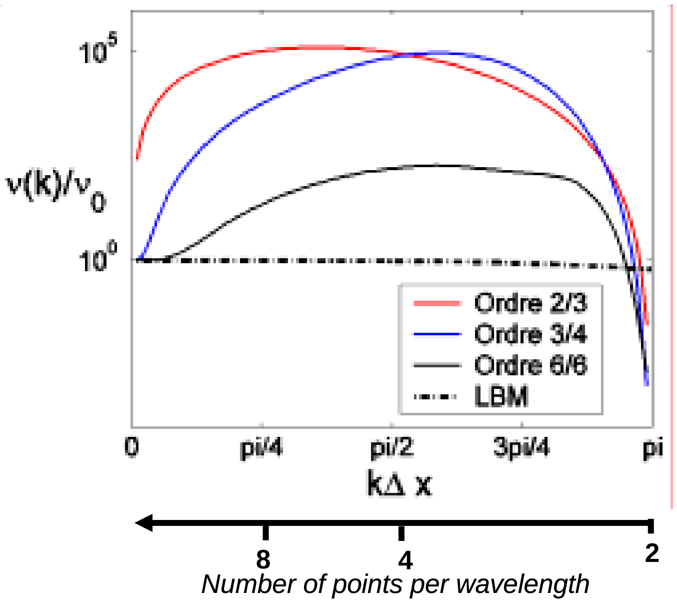
$$e^{-i\omega}\mathbf{U^n} \quad = \quad \mathbf{M}_\mathbf{d}^\mathrm{NS}\mathbf{U^n}$$

Comparison LBM vs finite difference Navier-Stokes schemes

Dispersion error



Dissipation error

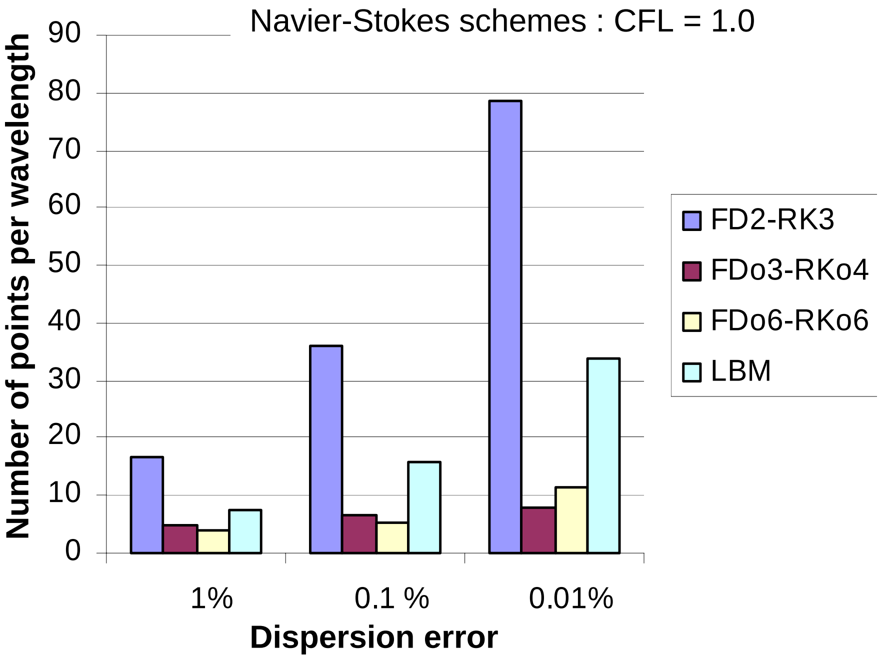


- **LBM has**
  - lower numerical dissipation than all aeroacoustic-optimized schemes
  - lower dispersion error than FD of order 2 in space and 3 in time (Runge-Kutta)
  - higher dispersion error than FD of order 3 in space and 4 in time (Runge-Kutta) and DRP (Dispersion Relation Preserving) optimized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

Marié, S., Ricot, D., Sagaut, P. (2009), J. Comput. Phys., 228



- 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)
  - Academic comparison of in-house LBM vs CFD++ : Geller, S., Krafczyk, M., Tölke, J., Turek, S., Hron, J. (2006): “Benchmark computations based on Lattice-Boltzmann, Finite Element and Finite Volume Methods for laminar Flows”, Computers and Fluids, 35

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
  - …

$\left.\begin{array}{l} \text{International Lattice Boltzmann Software Development Consortium} \\ \text{HemeLB} \end{array}\right\}$ Flow in human blood vessels

- **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 sofware**
  - **PowerFLOW, EXA Corp.**
  - MetaCFD, MetaHeuristics, USA (consulting only ?)
- **Industrial sofware**
  - LaBS (Lattice Boltzmann Solver), French industrial and academic Consortium

LaBS : Lattice Boltzmann Solver

Partners :

Industrial partners	Academics and labs
RENAULT MATELYS acoustique & vibrations SIGNAL DEVELOPPEMENT CS AIRBUS Oxalya	ONERA ENS LYON LABORATOIRE DE PHYSIQUE Institut Jean le Rond d'Alembert Département de Mathématiques d'Orsay

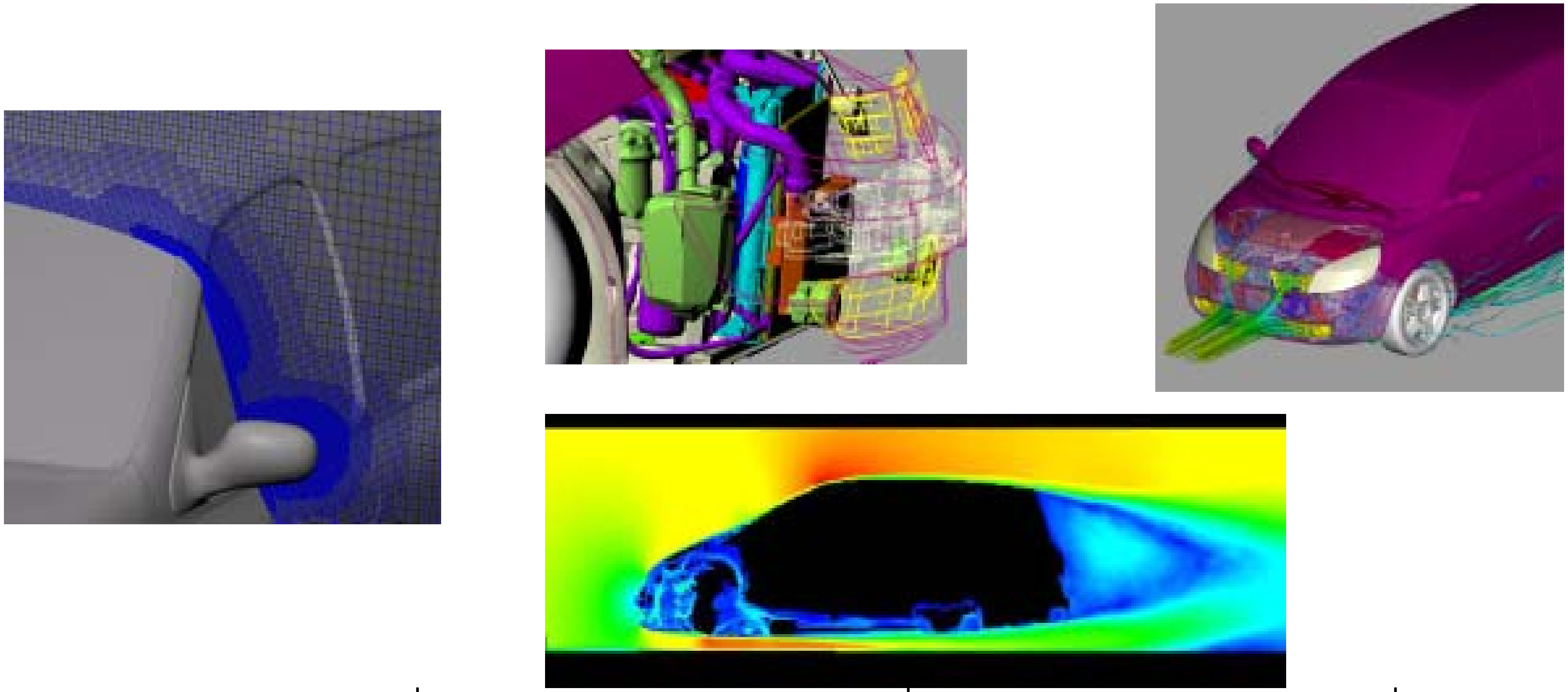
- Three-year project (2009-2012) funded by the french ministry of industry and the region Iles de France with support of competitiveness clusters:

mov'eo SYSTEM@TIC PARIS-REGION Pôle MTA LYON URBAN TRUCK & BUS

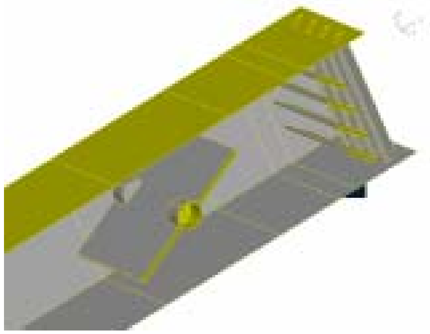
- Lattice Boltzmann Method
- Large Eddy Simulation approach
- Optimization for massively parallel computing
- Simultaneous simulation of aerodynamic noise sources and their acoustic propagation

PowerFLOW – current version

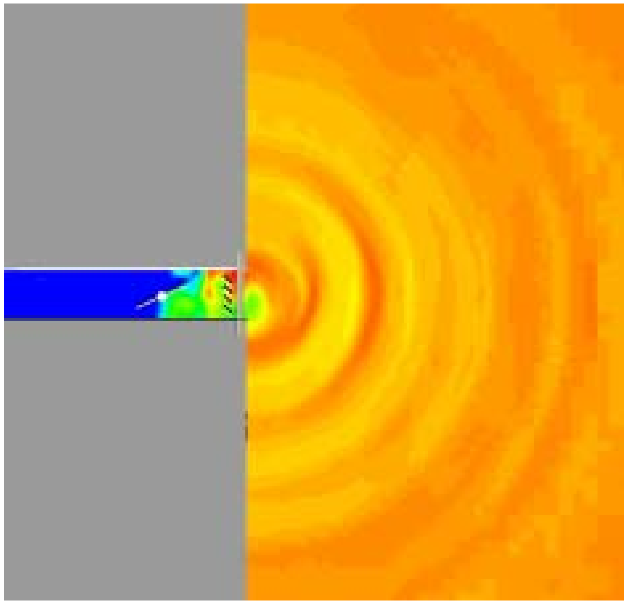
- LBM D3Q19 BGK with some adaptations
- Immersed frontiers for complex geometry (volumetric formulation)
- Turbulence model
  - Modified (Yakhot & Orszag, not published) $k-\varepsilon$ RNG model (Yakhot & Orszag, 1986)
  - Modified (adverse pressure gradient effects) log-law wall model
- Stability control with turbulence model + threshold numerical viscosity
- Parallel computations
  - <u>Tens of millions of cells</u> calculated for <u>hundreds of thousands of time-steps</u> on <u>tens of CPU</u> in a <u>few days</u>

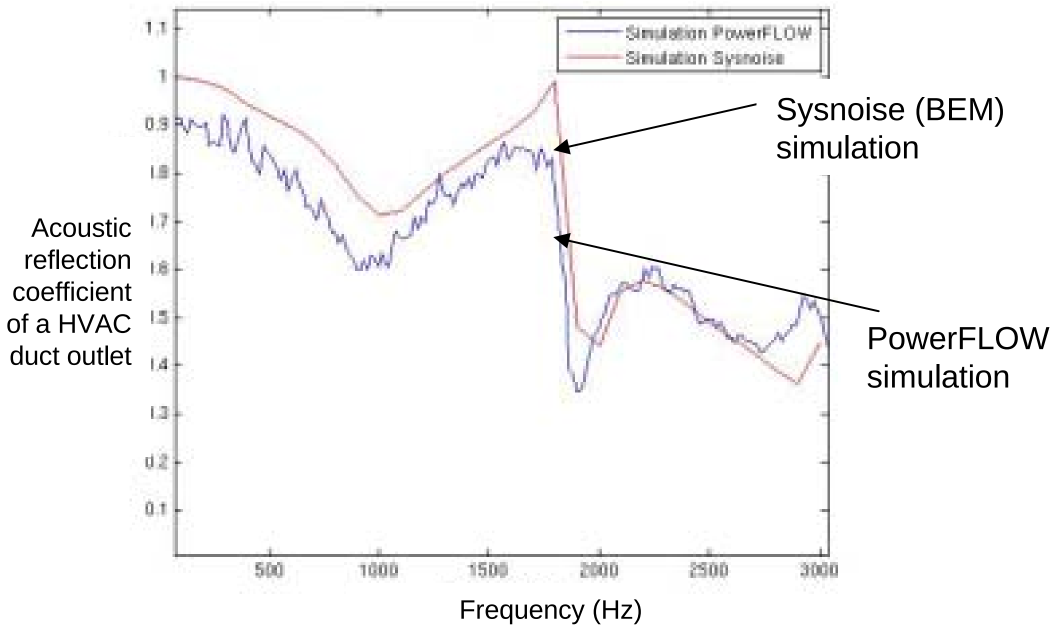


Acoustic impedance of outlets, without mean flow



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



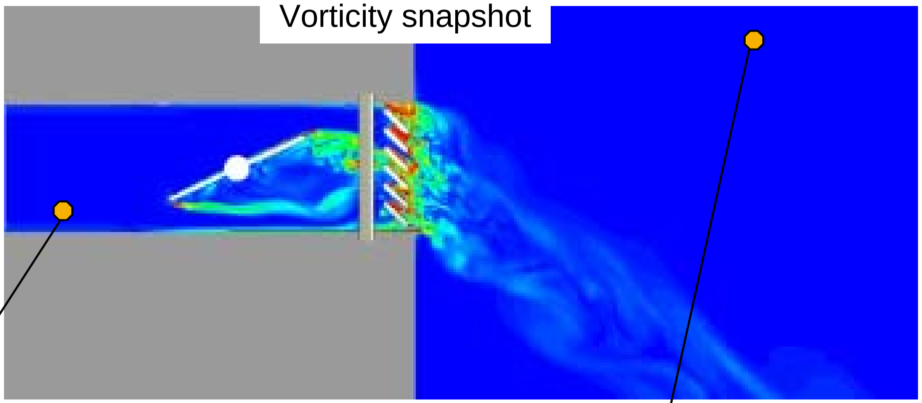


(J.-L. Adam et al., Acoustics’08, Paris)

Aerodynamic noise generated by HVAC vents

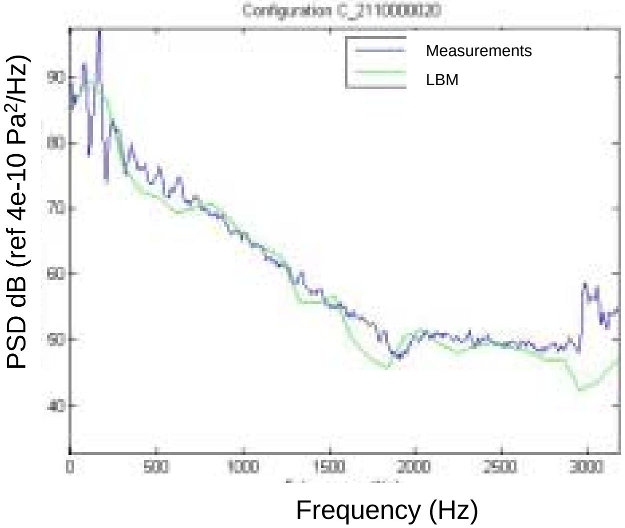
$U_0 = 18 \text{ m/s}$

Vorticity snapshot

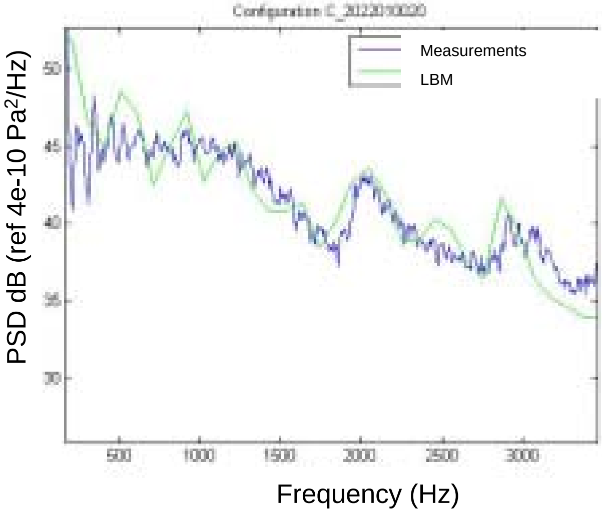


(J.-L. Adam et al., Acoustics'08, Paris)

Upstream acoustic pressure



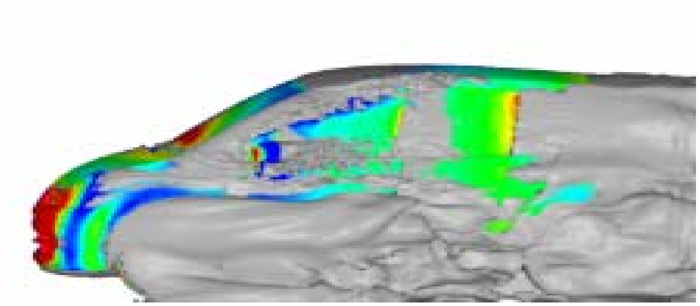
Downstream acoustic pressure

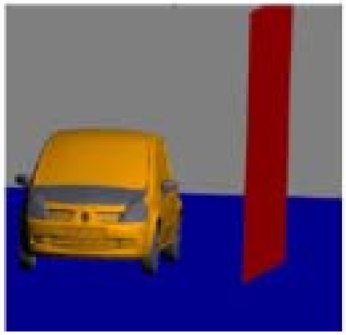


Direct aeroacoustic source identification based on LBM and beamforming technique

(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**

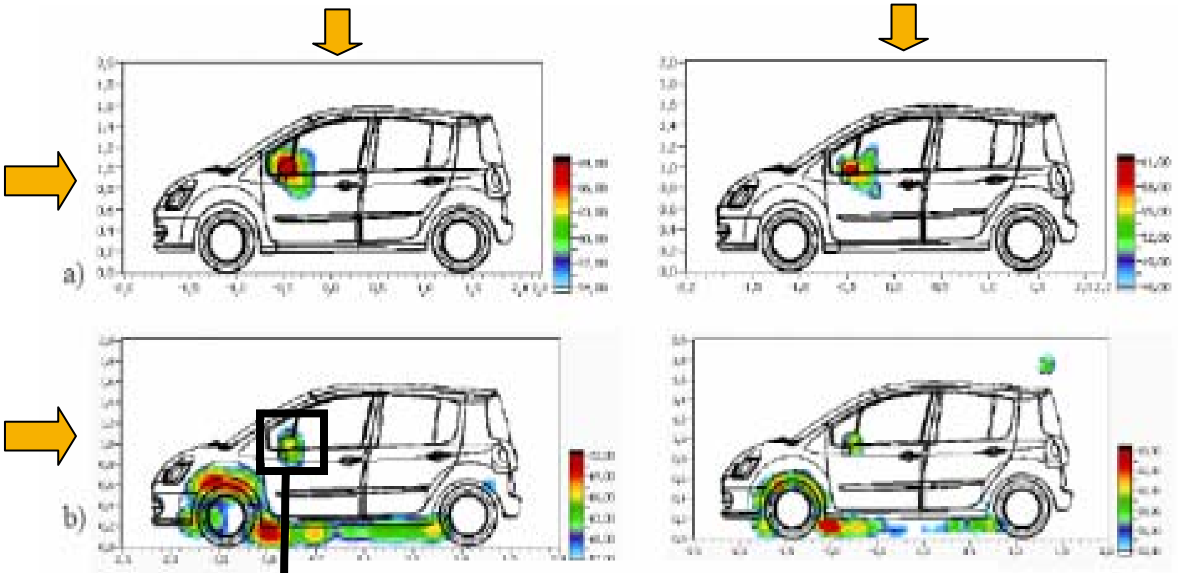
Direct aeroacoustic source identification based on LBM and beamforming technique

1/3 octave band 1000 HZ

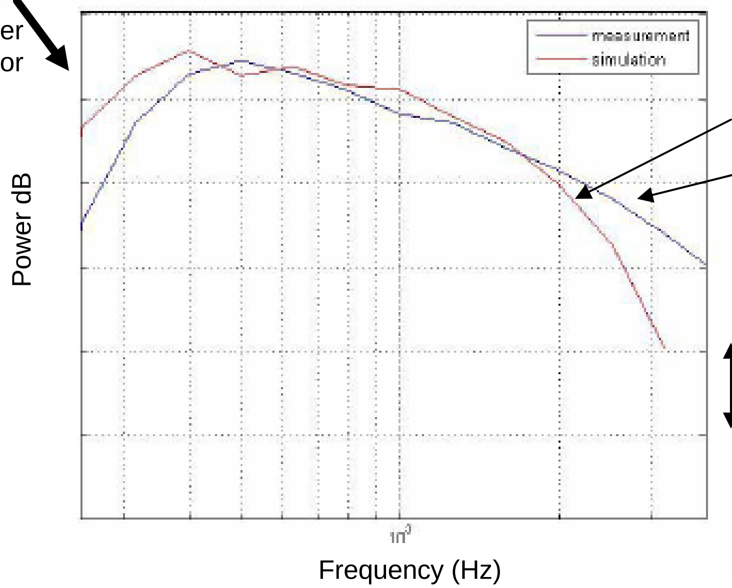
1/3 octave band 1600 HZ

Simulations

Measurements



Spatial integration of acoustic power around the side view mirror



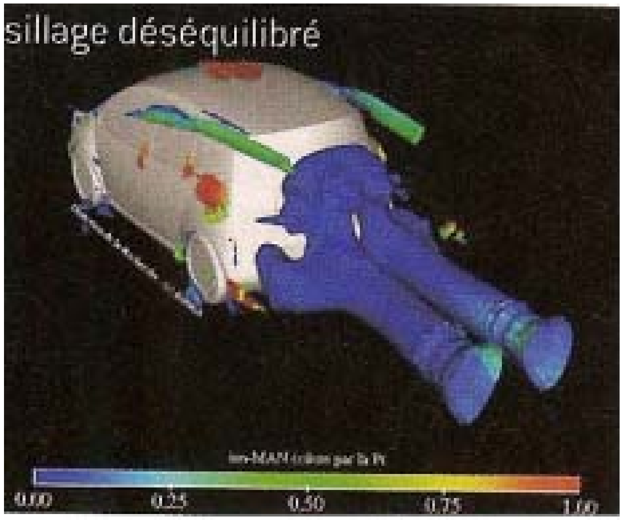
Simulation

Experiments

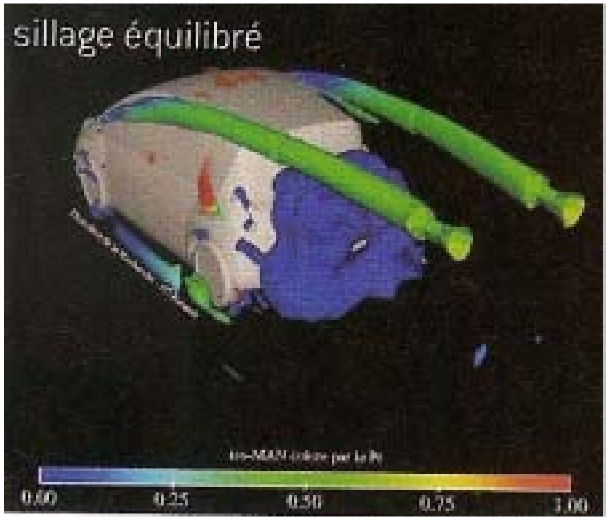
10 dB

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

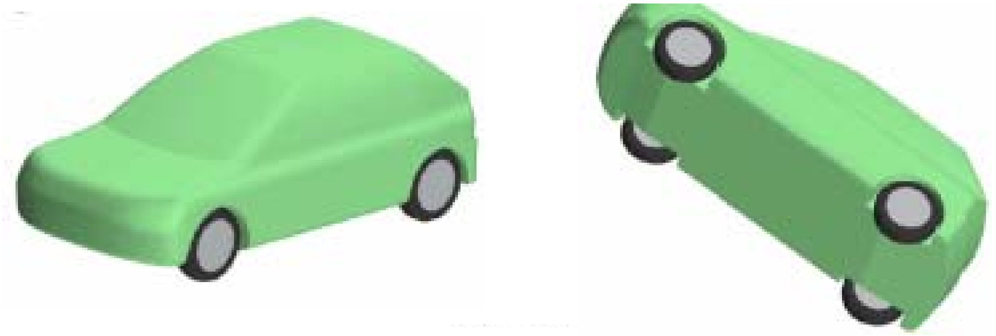


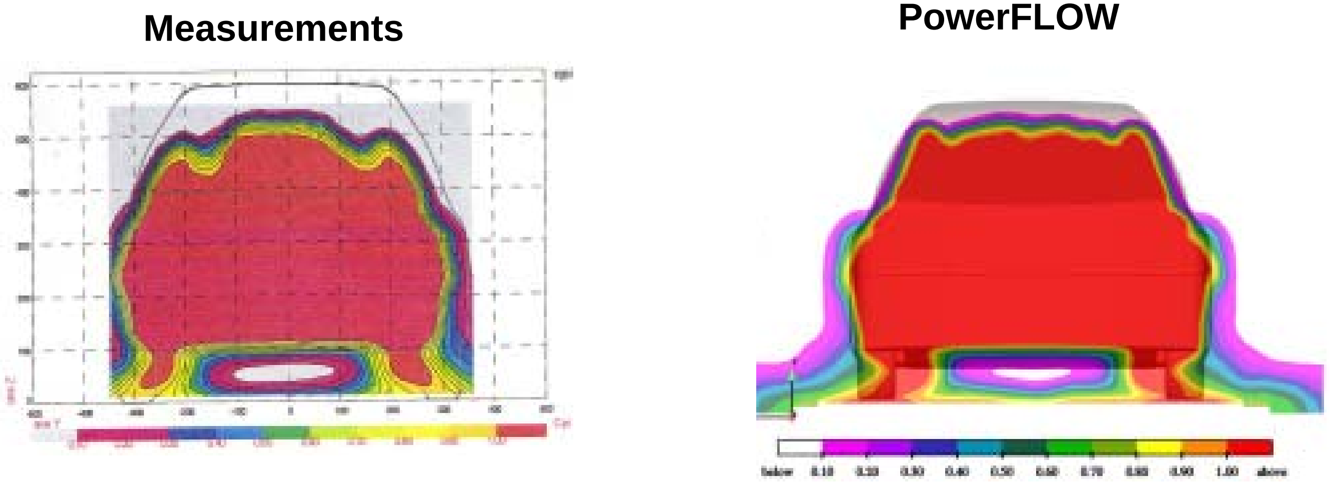
“2D” wake
→ Low drag

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

Validation of aerodynamic drag simulation

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





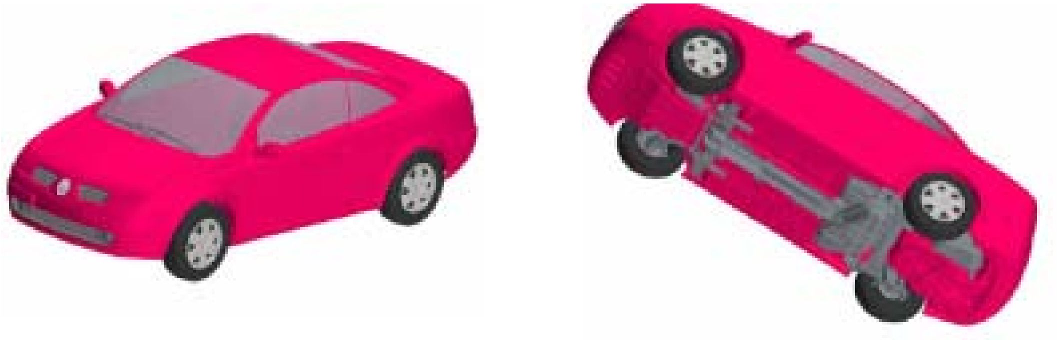
Measurements

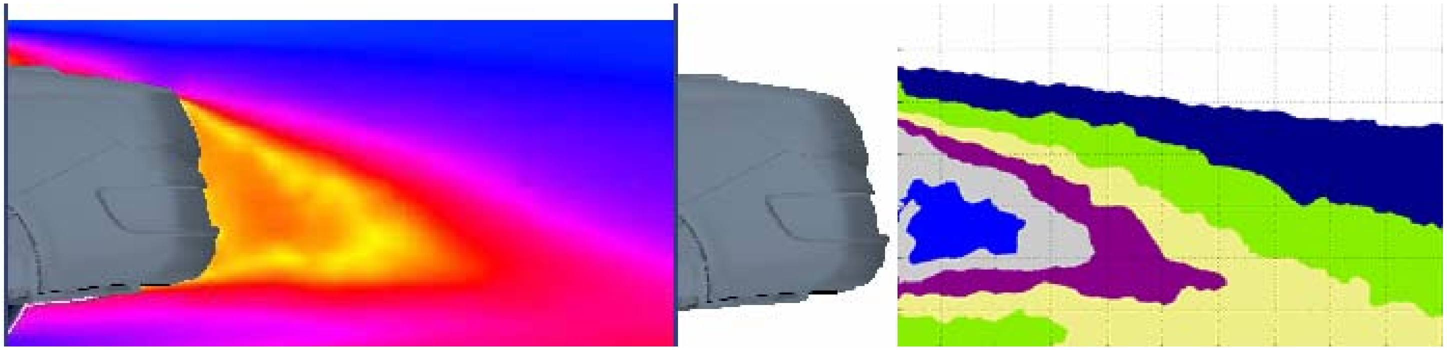
PowerFLOW

<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



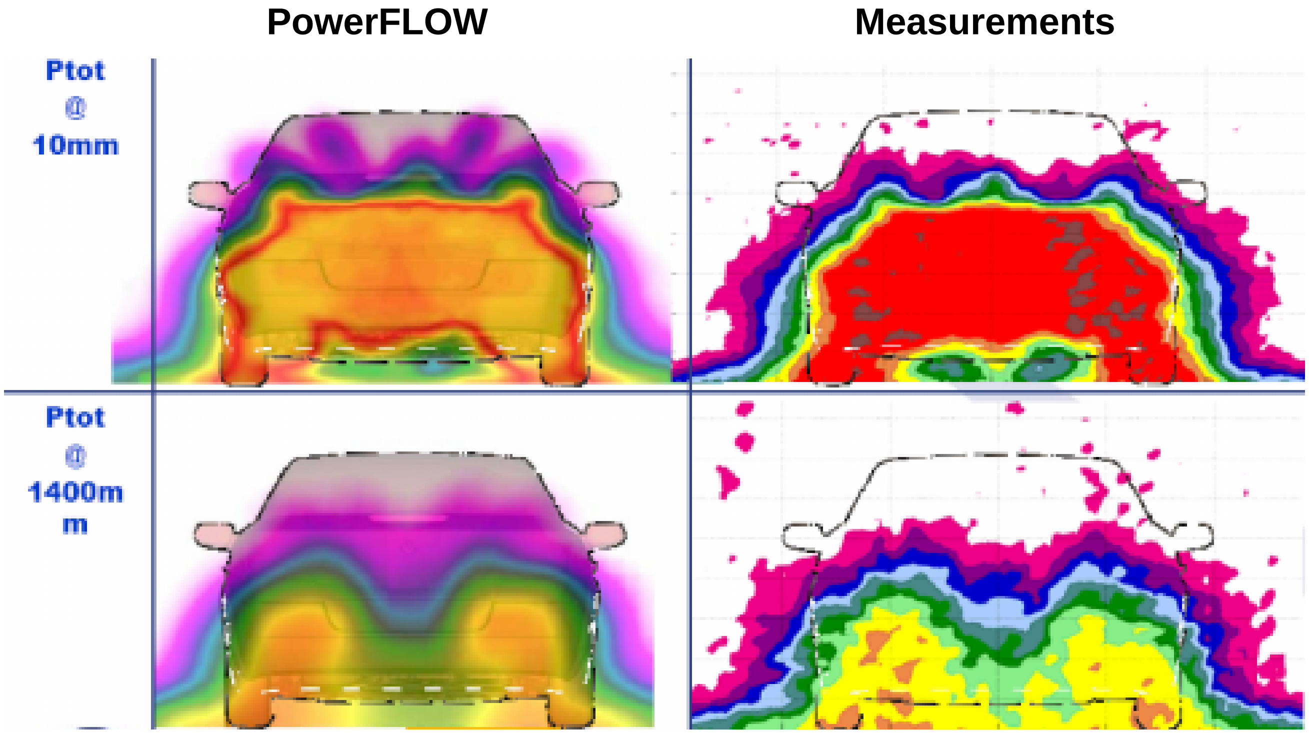


PowerFLOW **Measurements**

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

Validation of aerodynamic drag simulation

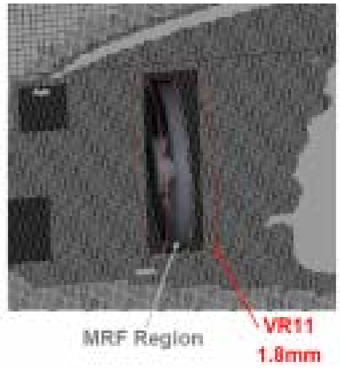
- **Validation on Megane CC**
  - Drag and lift coefficients are well recovered within few percents



Total pressure loss in the Megane CC wake

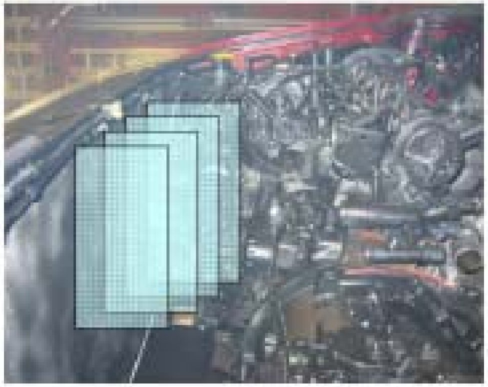
Underhood flow

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

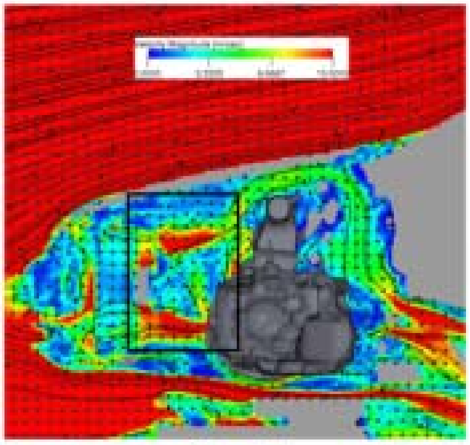


- **Experimental validation based on PIV measurements**

O. Bailly et al., SIA, Lyon 2005

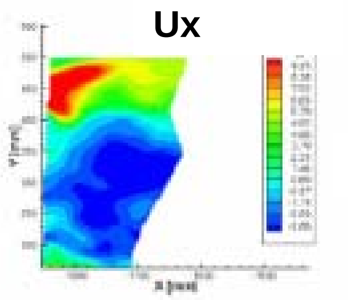


PIV measurements

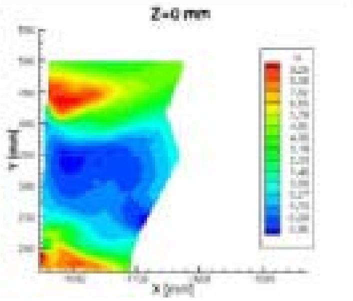


PowerFLOW

Ux

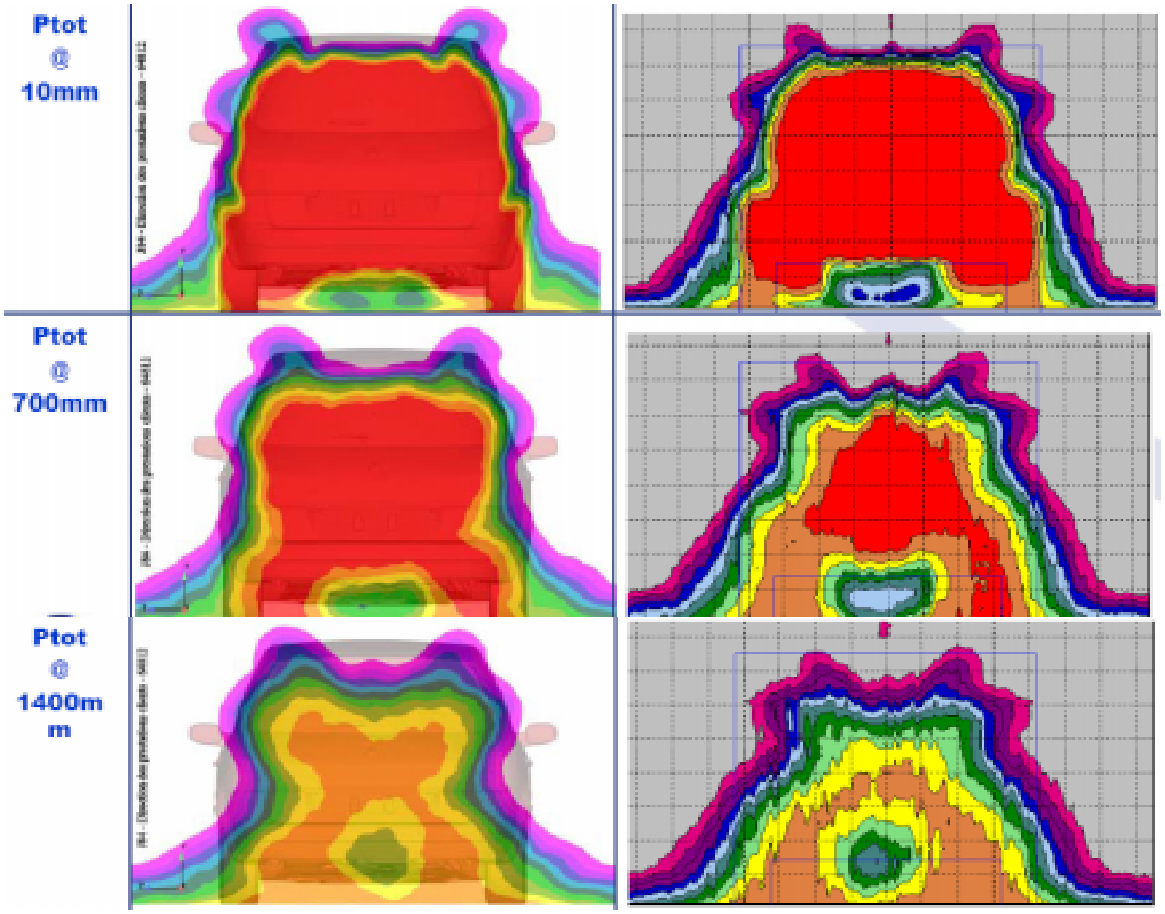


Measurements



PowerFLOW

Validation of aerodynamic drag simulation with underhood flow



PowerFLOW **Measurements**

<u>Total pressure loss in the Scenic wake</u>

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 aeroacoutic 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