LaBS
Lattice Boltzmann Solver

Aeroacoustic computations with a new CFD solver based on the Lattice Boltzmann Method

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SIA, Automotive and Railway Comfort conference, Le Mans, october 24 & 25, 2012

LaBS project

LaBS Consortium

Three industrial companies and two scientific laboratories, software's co-owner and developpers, leading, supporting and validating LaBS.

A collaborative project with strong partnerships

« LaBS Consortium » collaborates with partners whose scientific expertise enables building mathematical models and establishing simulation best-practices for several application domains.

With the support of competitiveness clusters :

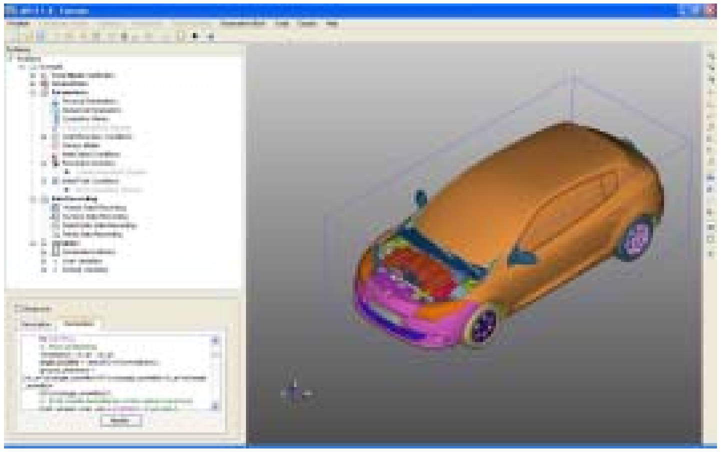
Financial support from FUI8 :

Period : 2009-2013

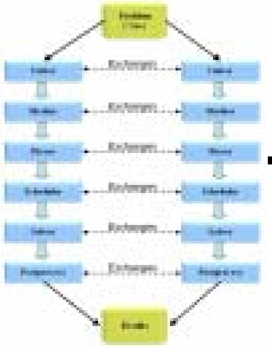
LaBS software

- ❑ Developed from scratch
  - a GUI for simulation setup
  - a parallel solver, including the volumetric mesher

Surface meshes (e.g. : stl files)



Problem file : *.labs



Results files
- Paraview format
- Ensight format

GUI

Parallel solver

LaBS software

Lattice Boltzmann Method

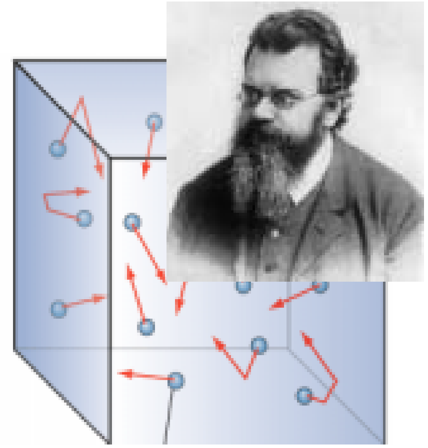
Statistical mechanics

- **Boltzmann equation**
- **Particles**
  - ***Kinetic energy***
  - ***Momentum***
  - ***Shocks***
  - ***Mean free path***

Chapman-Enskog theoretical expansion

Continuum mechanics

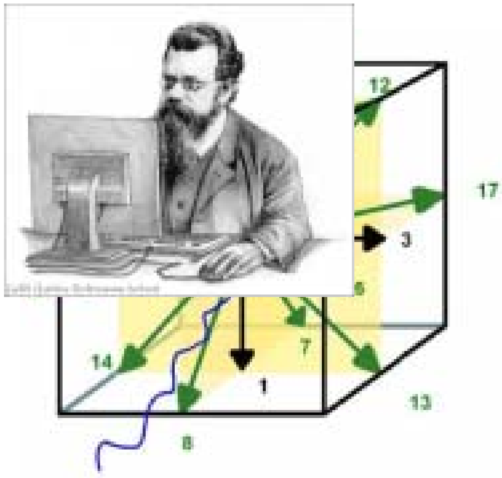
- **Navier-Stokes equations**
- **Continuous media**
  - ***Temperature***
  - ***Pressure***
  - ***Density***
  - ***Viscosity***



Lattice Boltzmann method

- Particle velocity discretization (finite discrete velocity set for particles instead of continuous particle velocity)
- Space and time discretizations of the discrete velocity Boltzmann equation

Chapman-Enskog theoretical expansion → Navier-Stokes equations



Main numerical issues

Calculation of distribution functions on a cartesian mesh

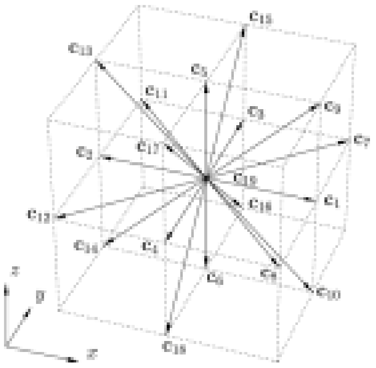
$$f_\alpha(\vec{x}+\vec{c}_\alpha\Delta t, t+\Delta t)=\left(1-\frac{1}{\tau}\right)f_\alpha(\vec{x},t)+\frac{1}{\tau}f_\alpha^{eq}\left(\rho(\vec{x},t),u(\vec{x},t)\right) \longrightarrow$$

Standard fluid mechanics variables
on the same mesh

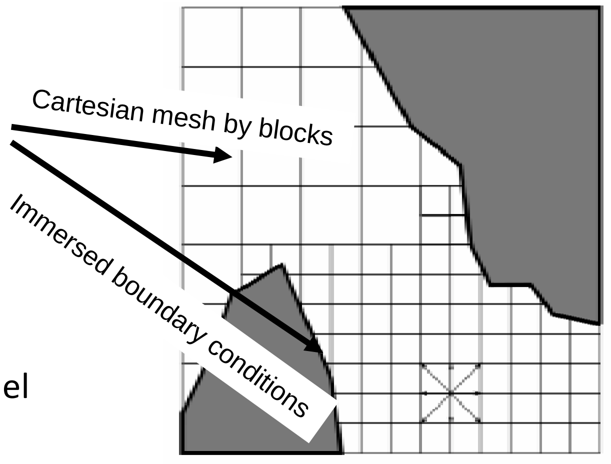
$$\begin{cases}\rho(\vec{x},t)=\sum_\alpha f_\alpha(\vec{x},t)\\ \rho(\vec{x},t)\vec{u}(\vec{x},t)=\sum_\alpha \vec{c}_\alpha f_\alpha(\vec{x},t)\end{cases}$$

$$p(\vec{x},t)=c_s^2\rho(\vec{x},t)$$

$$c_s=\frac{1}{\sqrt{3}}\frac{\Delta x}{\Delta t} \qquad \nu=c_s^2\left(\tau-\frac{\Delta t}{2}\right)$$



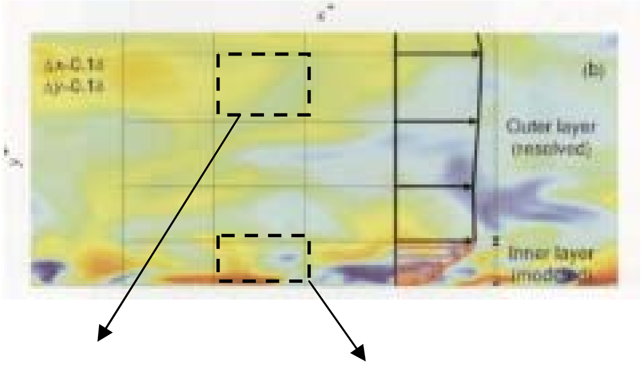
19 discrete velocity model
used in LaBS



Cartesian mesh by blocks

Immersed boundary conditions

Spatial discretization → unresolved
turbulent scales

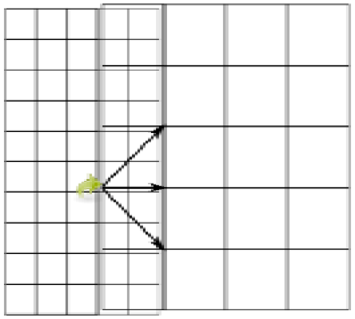


Sub-grid turbulence model

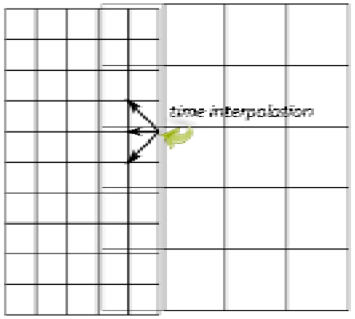
Wall model if too coarse
mesh near walls

Mesh refinement

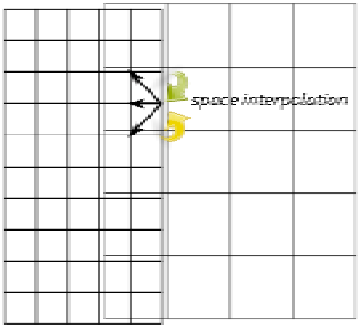
- AMR-like mesh : successive refinement of the volume mesh (M. J. Berger and P. Colella, "Local adaptive mesh refinement for shock hydrodynamics," J. Comp. Phys, 82:64-84, 1989)
- In LaBS : vertex-centered formulation → coarse mesh nodes are coincident with fine mesh nodes
- Partial mesh overlapping approach for data exchanges between refinement blocks
- Need for rescaling of distribution functions (O. Fillipova and D. Hänel. Grid refinement for lattice-BGK models. J. Comput. Phys., 147(1):219–228, 1998)



Fine to coarse mesh transfer

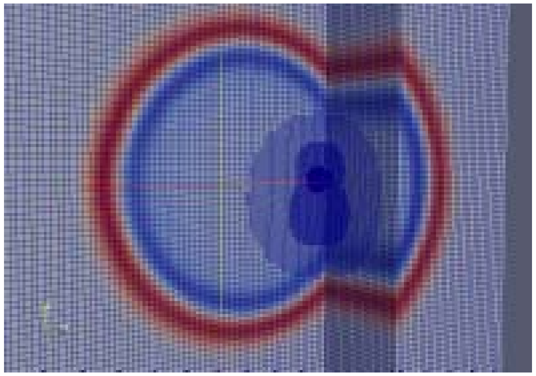


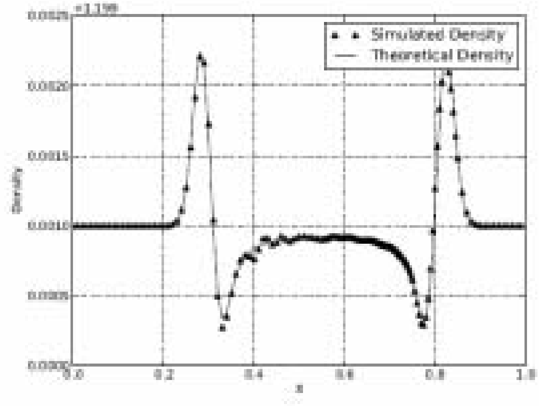
Coarse to fine mesh transfer for coincident fine nodes



Coarse to fine mesh transfer for non-coincident fine nodes

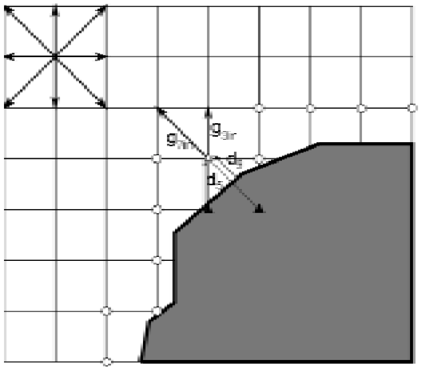
- Example of validation for an acoustic pulse propagation in a multi-resolution grid





Immersed boundary condition

- ❑ Full separation between the octree volumetric mesh and the surface mesh (triangles)
- ❑ Immersed boundary algorithm must be developed. Several available approaches in literature deduced from the original Navier-Stokes techniques (Peskin, 1977). See for example : *Z.-G. Feng and E.E. Michaelides. The Immersed Boundary-Lattice Boltzmann Method for Solving Fluid-Particles Interaction Problems. J. Comput. Phys., 195(2):602-628, 2004*



Distribution functions associated with velocity #7 and velocity #3 in its example can not calculated by the collision / propagation LBM algorithm because neighbor nodes are inside the solid

- ❑ In LaBS : vertex-based formulation based on the reconstruction of the distribution functions from the macroscopic data (pressure, velocity and velocity gradients) :

$$f_\alpha(\vec{x},t) = f_\alpha^{eq}(\vec{x},t) + f_\alpha^{neq}(\vec{x},t) = \underbrace{\omega_\alpha \rho \left(1 + \frac{c_{\alpha,i} u_i}{c_s^2} + \frac{u_i u_j \left(c_{\alpha,i} c_{\alpha,j} - c_s^2 \delta_{ij}\right)}{2 c_s^4}\right)}_{\rho,\ u_i} + \underbrace{\tau \frac{\omega_\alpha \rho}{c_s^2} \sum_{ij} \left(c_{\alpha,i} c_{\alpha,j} - c_s^2 \delta_{ij}\right) S_{ij}}_{S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)}$$

(Chapman-Enskog expansion)

Spatial interpolation

Calculation of velocity gradients by off-centered finite difference scheme

Similar to the model described in : J.C.G. Verschaeve and B. Müller, "A curved no-slip boundary condition for the lattice Boltzmann method", J. Comput. Physics, 2010, 229(19), pp.6781-6803

Turbulence model

- Sub-grid turbulent vortices must be modeled by a turbulence model
- Lattice Boltzmann is a native unsteady algorithm with very low numerical dissipation : it is well adapted to Large Eddy Simulation approach
- Large scales that ensure turbulent mixing are directly calculated, only the dissipative effect of small turbulent scales must be added.
- Two sub-grid models are implemented in LaBS :
  - Shear-Improved Smagorinsky Model (SISM)
  - The Approximate Deconvolution Model (ADM)

- The shear-improved Smagorinsky model is a sub-grid turbulent viscosity model :
  - *E. Leveque, F. Toschi, L. Shao and J.-P. Bertoglio, Shear-Improved Smagorinsky Model for Large-Eddy Simulation of Wall-Bounded Turbulent Flows, Journal of Fluid Mechanics 2007, vol. 570, pp. 491-502*

$$f_\alpha(\vec{x}+\vec{c}_\alpha\Delta t, t+\Delta t) = \left(1-\frac{1}{\tau}\right) f_\alpha(\vec{x},t) + \frac{1}{\tau} f_\alpha^{eq}\left(\rho(\vec{x},t), u(\vec{x},t)\right) \longrightarrow \nu = c_s^2\left(\tau - \frac{\Delta t}{2}\right)$$

$$\nu_{eff} = \nu + \nu_T \longrightarrow \tau_{eff}$$

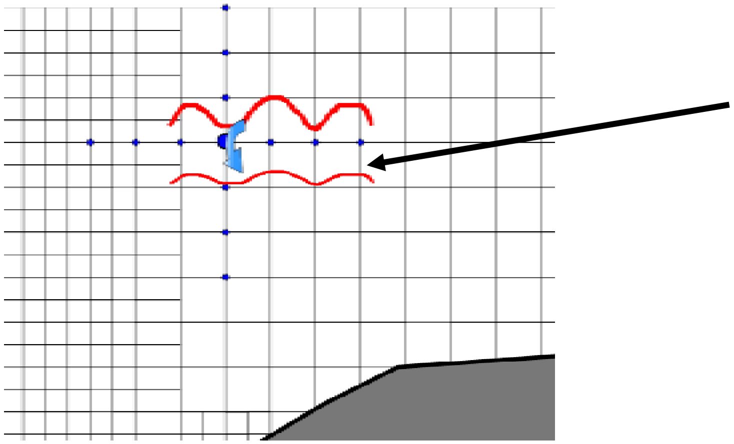
$$\nu_T = (C_s\Delta)^2 \cdot \left(|\mathbb{S}| - |\langle\mathbb{S}\rangle|\right)$$

$$\mathbb{S}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad |\mathbb{S}| \equiv \sqrt{2\sum_{i,j}\mathbb{S}_{ij}\mathbb{S}_{ij}}$$

"< >" is low-pass filtering based on an exponentially-weighted moving time average

Turbulence model

- ☐ The Approximate Deconvolution Model (ADM) is not a turbulent viscosity model : dissipation is added through selective spatial filtering
  - ☐ *Navier-Stokes : Stolz S, Adams NA, Kleiser L. An approximate deconvolution model for large-eddy simulation with application to incompressible wall-bounded flows. Phys Fluids 2001;13:997–1015*
- ☐ Validation of ADM for LES simulations have been done with Navier-Stokes solver (Bogey, C. & Bailly, C., 2006, Computation of a high Reynolds number jet and its radiated noise using large eddy simulation based on explicit filtering, Computer & Fluids, 35(10), 1344-1358) and LBM solver (Lattice Boltzmann : O. Malaspinas and P.Sagaut, Advanced large-eddy simulation for lattice Boltzmann methods: The approximate deconvolution model Phys. Fluids 23, 105103, 2011)
- ☐ LBM algorithm is unchanged compared to the DNS case : only an explicit filtering step is added

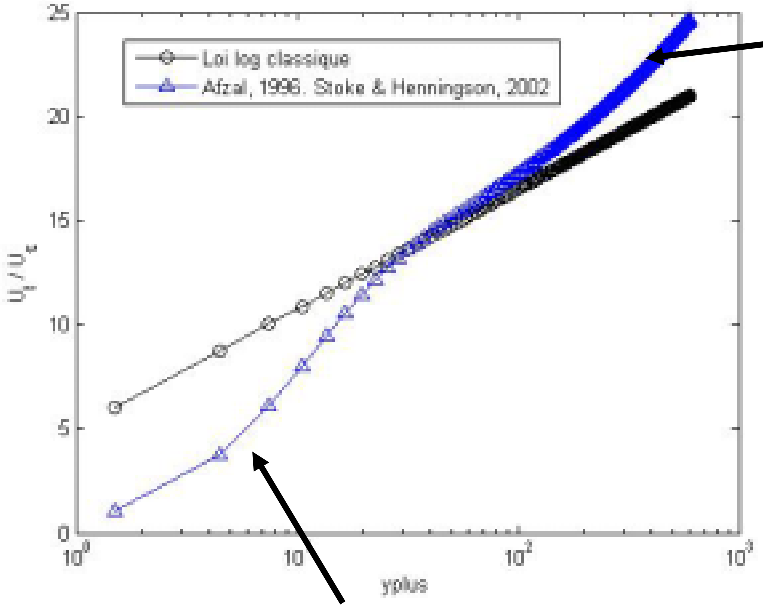


Small scales are damped without affecting the larges scales

- ☐ In LaBS : 7 point stencil is used : D. Ricot, S. Marié, P. Sagaut, C. Bailly Lattice Boltzmann method with selective viscosity filter, Journal of Computational Physics 228 (2009) 4478–4490

Turbulence model

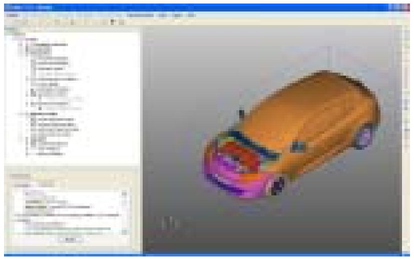
- Both Shear-Improved Smagorinsky model and Approximate deconvolution model can be associated with a wall law model
- The wall law is a lag-law with adverse pressure gradient effects proposed by Afzal : N. Afzal. Wake layer in a turbulent boundary layer with pressure gradient: a new approach. In IUTAM Symposium on Asymptotic Methods for Turbulent Shear flows at High Reynolds Numbers. K., G., ed., Kluwer Academic Publishers, 1996, 95-118



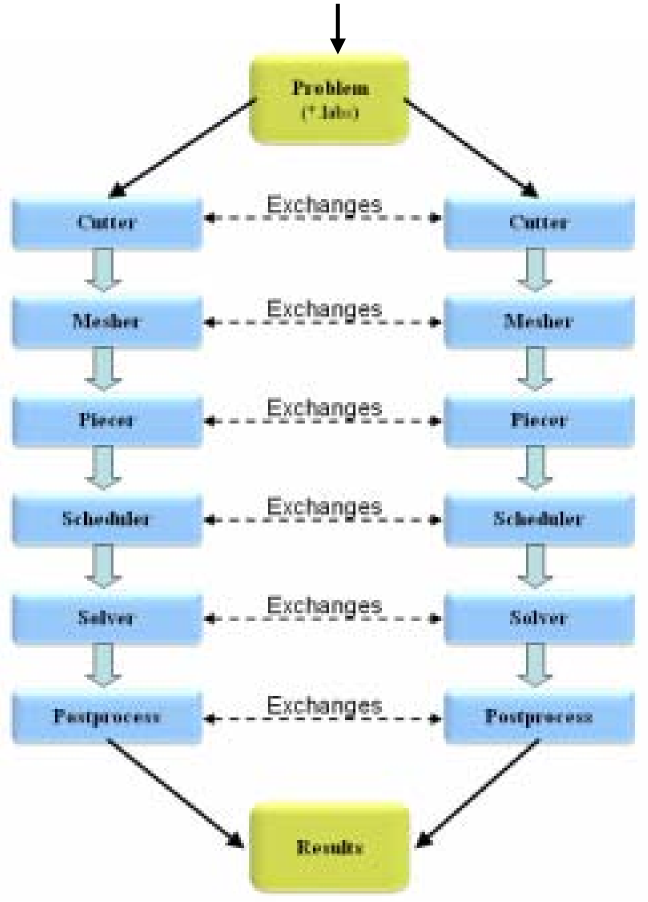
Pressure gradient effect

Viscous sub-layer

Solver architecture



Simulation setup : dedicated GUI, with script capacities



Load balancing optimization

Mesh and data structure generation

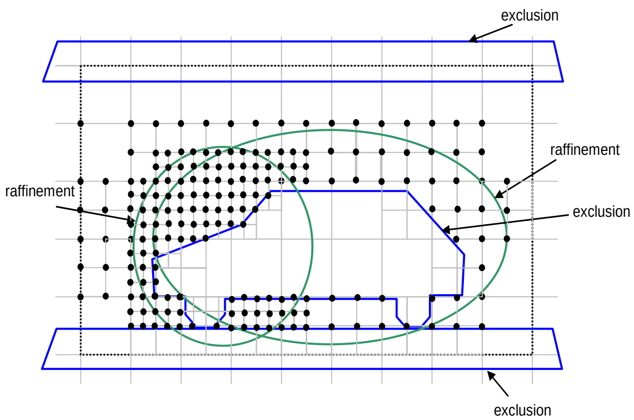
Computation scheduling

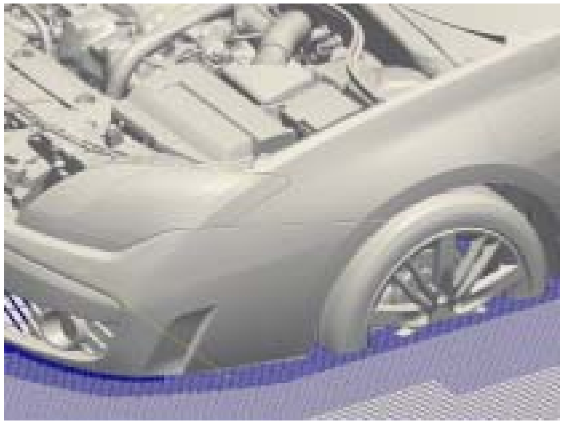
Time-step loop

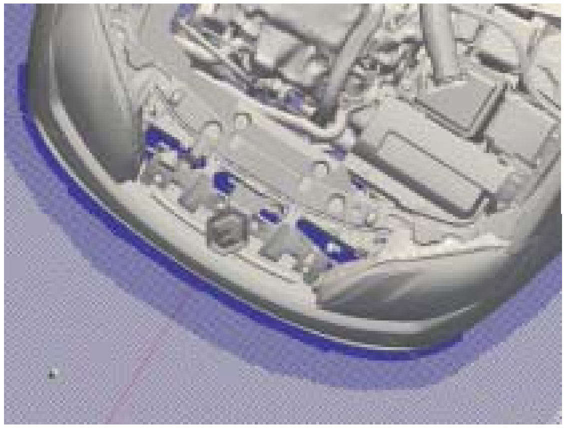
Merge / convert results files

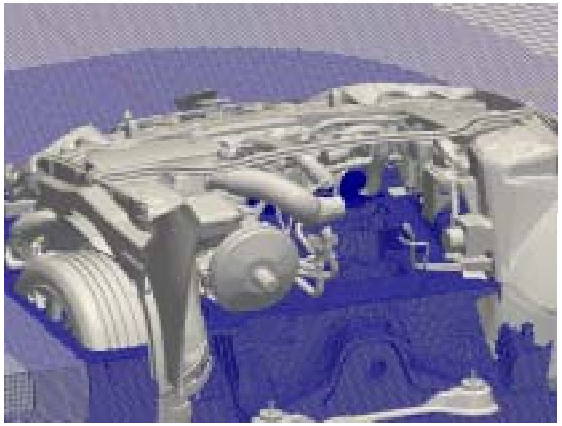
Volumetric mesh

- Based on efficient octree mesher
- Interior of surface meshes are excluded, without limitation in term of shape, number of surfaces, and overlapping regions

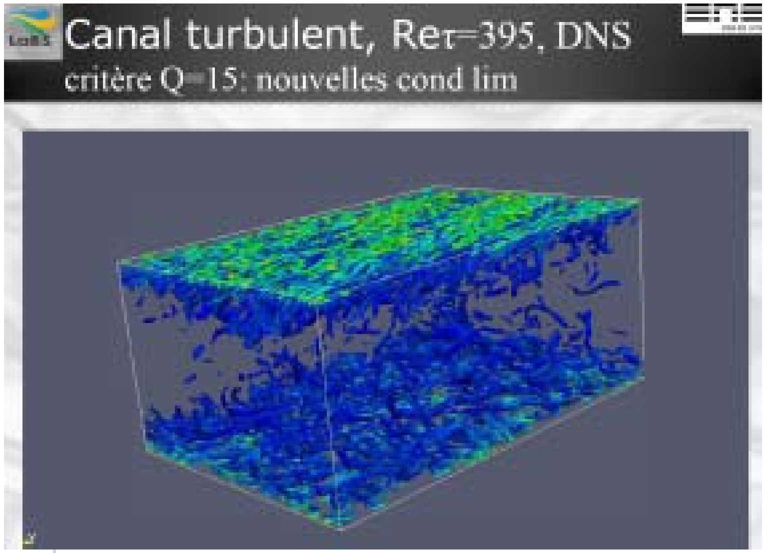








Academic validations : turbulent channel flow



Canal turbulent, Reτ=395, DNS
critère Q=15: nouvelles cond lim

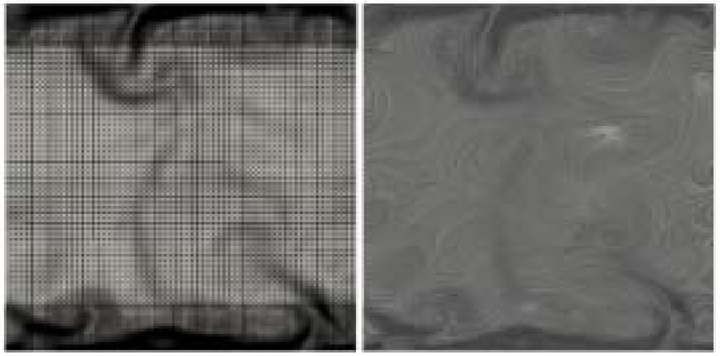


Figure 1. DNS of a turbulent plane-channel flow at $Re_\tau = 180$ by the Lattice-Boltzmann

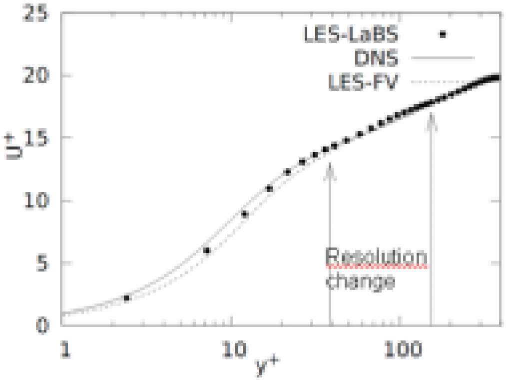


Figure 1: *Mean streamwise velocity; LaBS compared to DNS and classical LES; Channel flow,* $Re_\tau = 395$.

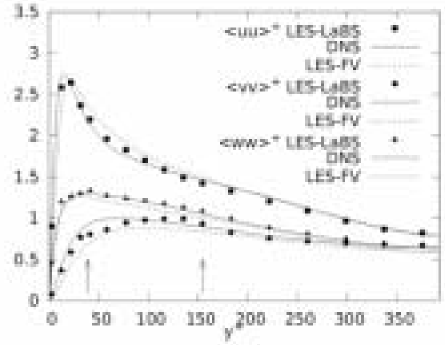
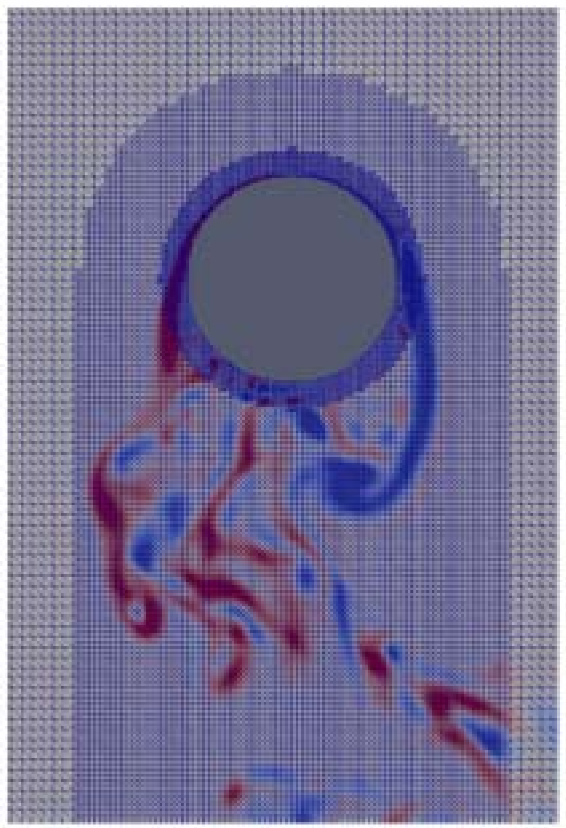
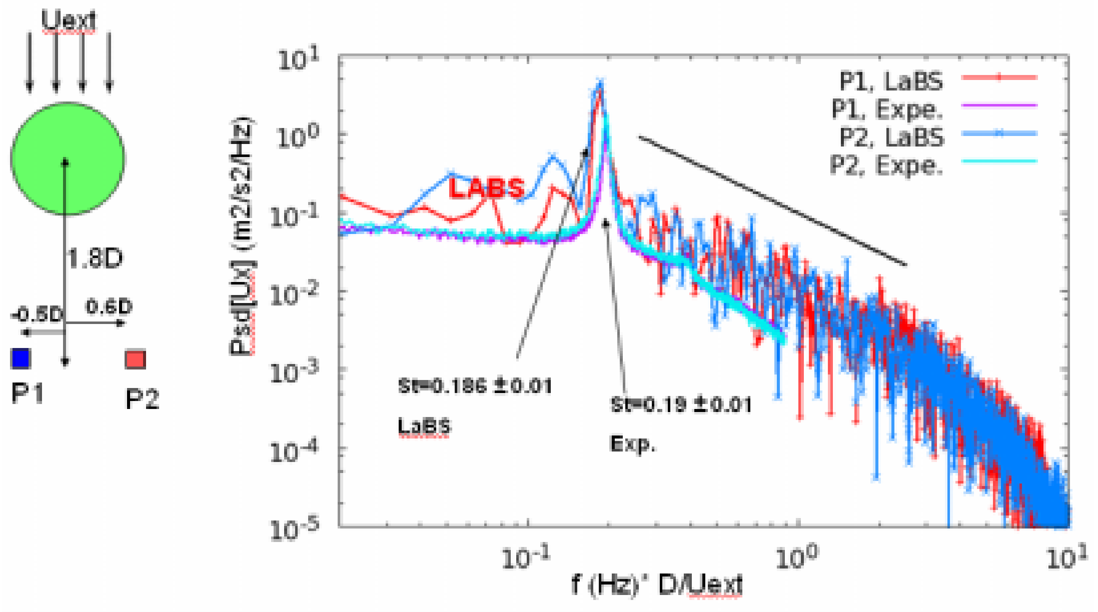


Figure 2: *Reynolds stress tensor, diagonal components; LaBS compared to DNS and classical LES. Channel flow,* $Re_\tau = 395$.

Academic validations : cylinder wake



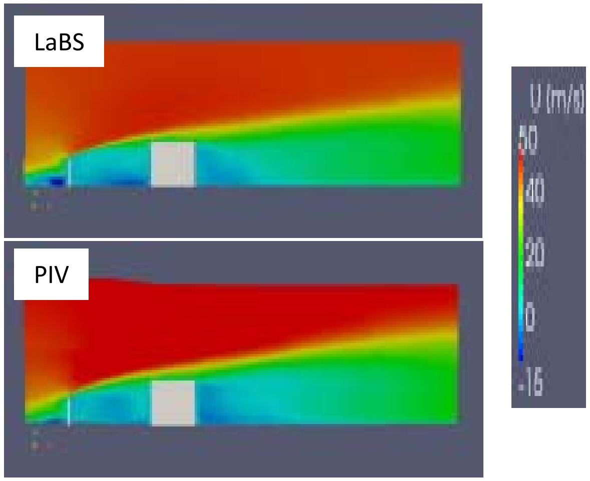
- Turbulent flow behind a circular cylinder, ReD = 47000



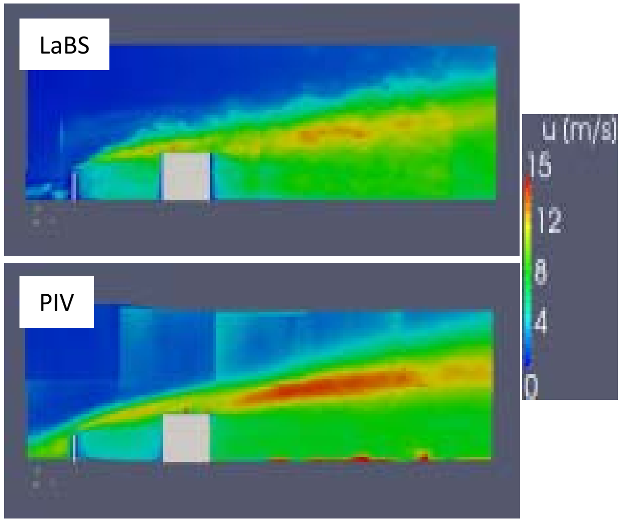
Validation on simple case : Fence-cube configuration

- Experimental database from a previous Predit project (MIMOSA) : measurements at LMFA / Ecole Centrale Lyon
- A cube (size 10 cm) mounted on a plane is placed behind a fence : PIV, hot-wire, unsteady wall pressure measurements
- U0=45 m/s, 20 millions mesh nodes, 350000 time-steps (around 0.78 sec of physical time)

Mean streamwise velocity

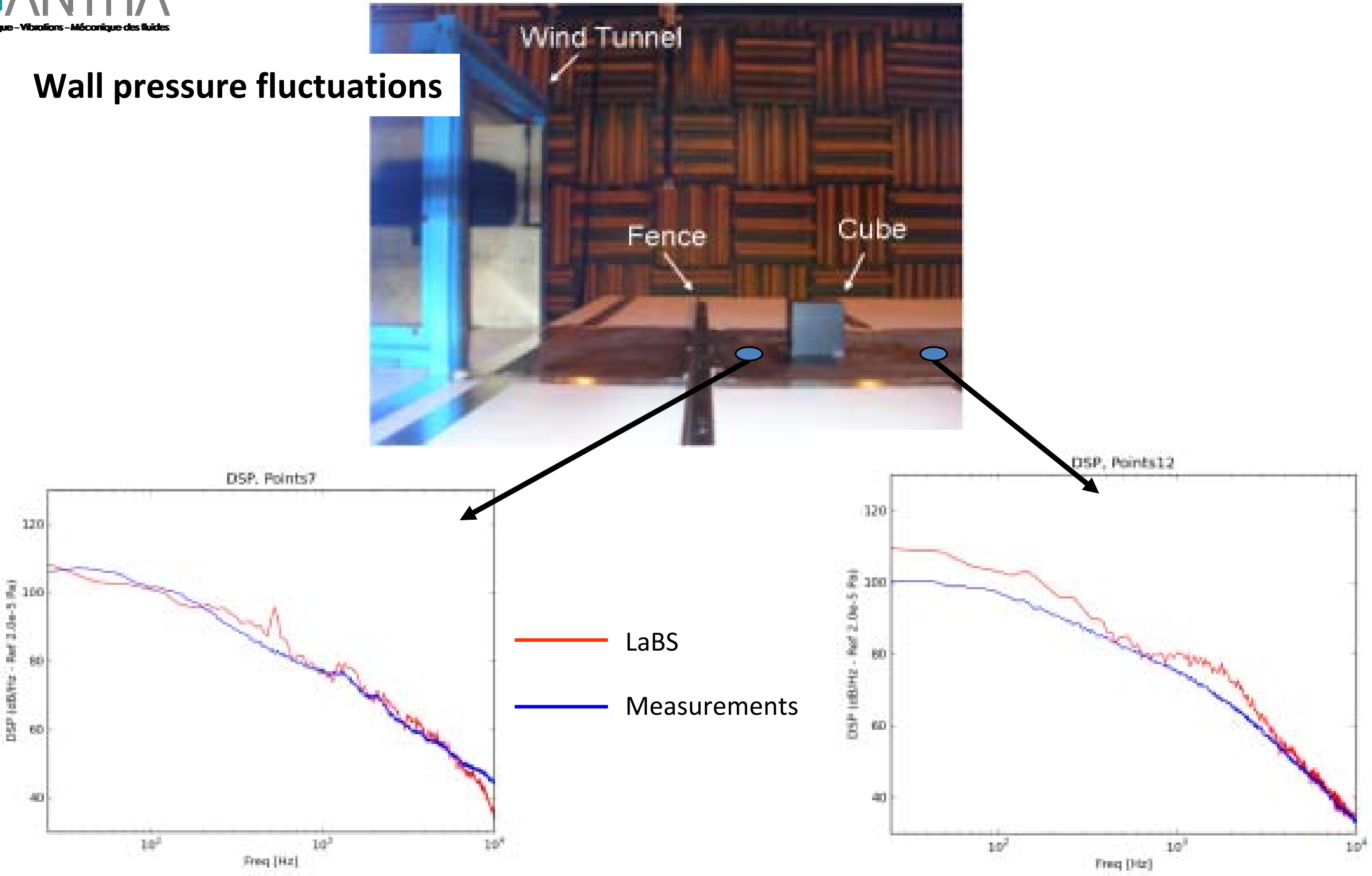


Fluctuating streamwise velocity

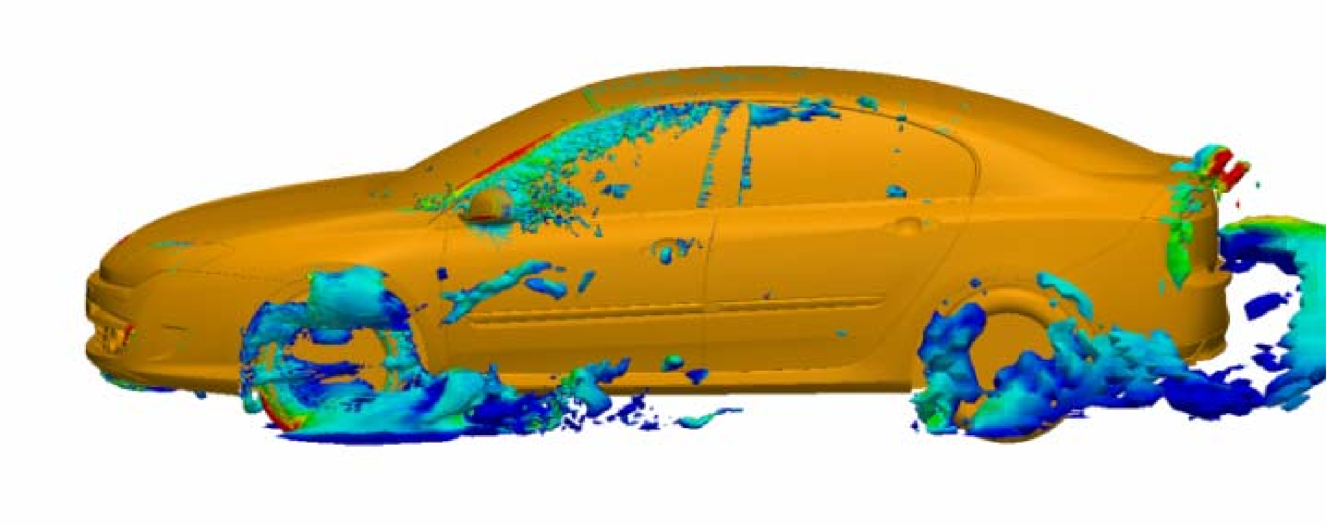


Validation on simple case : Fence-cube configuration

Wall pressure fluctuations



Validation on vehicles

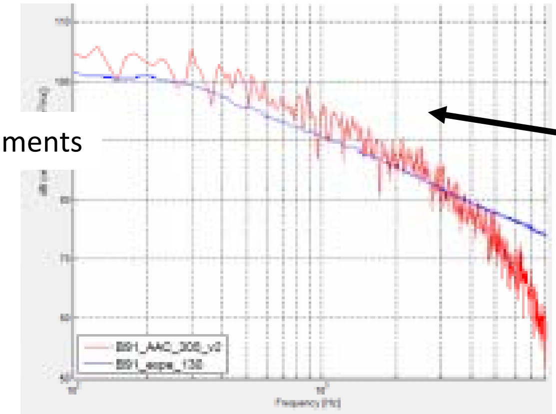


- ☐ Full scale vehicle simulation
- ☐ 10 levels of refinement, around 30 millions mesh nodes, 300 000 time-steps
- ☐ U0 = 44.4 m/s
- ☐ Wall Law LES (Approximate Deconvolution Model)

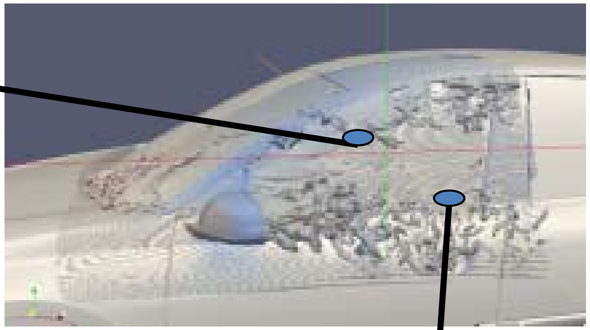
Validation on vehicles

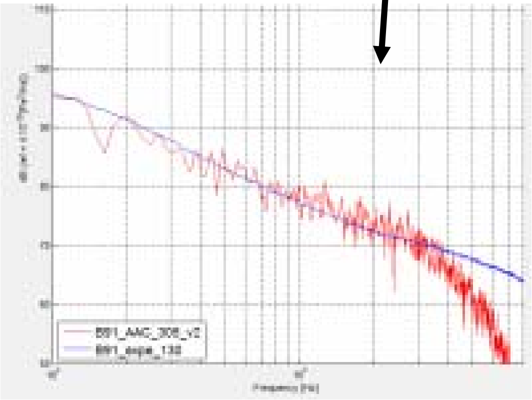
LaBS

Measurements

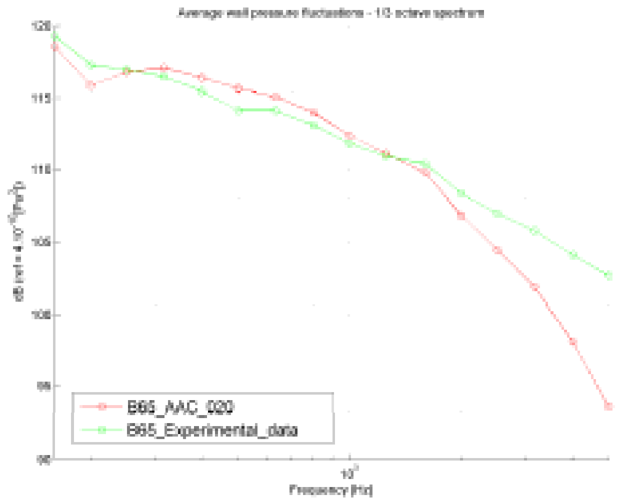


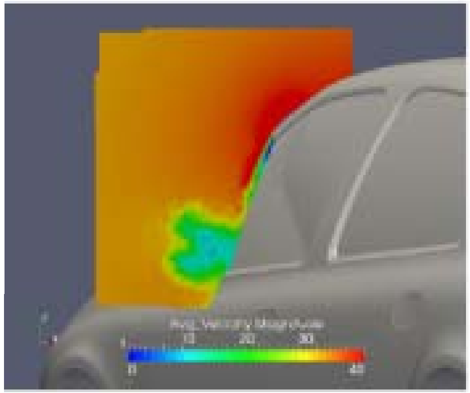
Laguna case : fine band spectra





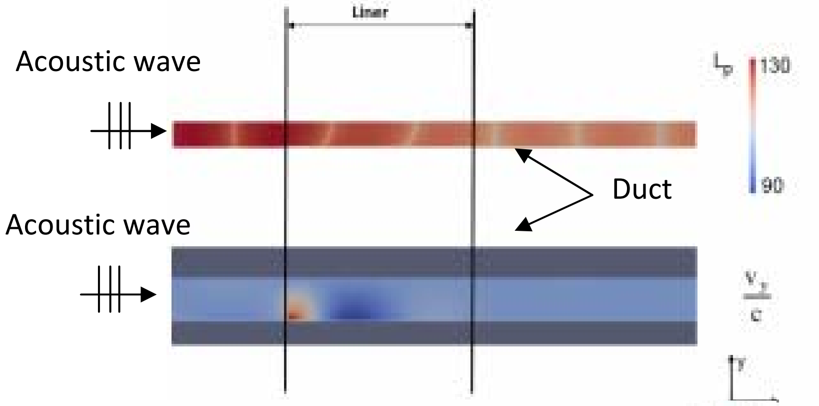
Clio case : third-octave band spectra, averaged
on the whole surface of the side window



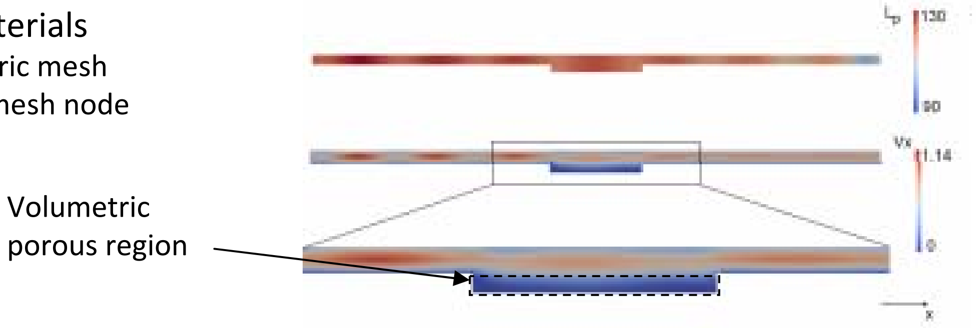


Innovative models : acoustic impedance and porous media

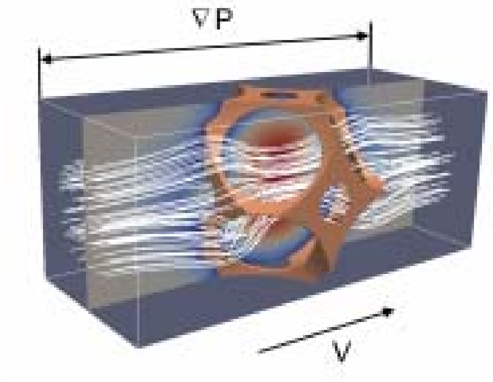
- Development of a time-domain locally reactive impedance



- Development of non-locally reactive porous materials
    - Porous materials is represented by a volumetric mesh
    - Darcy law (resistivity) can be applied on this mesh node to model low-frequency absorbing behavior



- Airflow resistivity characterization
    - Direct « measurement » of the air flow resistivity of a micro-structure of arbitrary complexity



Innovative models : moving solids

- Development of a general framework for moving solid models
  - Moving solid are embedded in a moving mesh
  - Displacement of mesh / solid is taken into account through the ALE (Arbitrary-Lagrangian Eulerian) model : at each time-step the previous data are interpolated on the mesh at its new position
  - Fixed / mobile mesh data exchanges are treated with Chimera approach (overlapping grid)
- Rotating solids are first developed in LaBS

Rotating cube

Oscillating cube

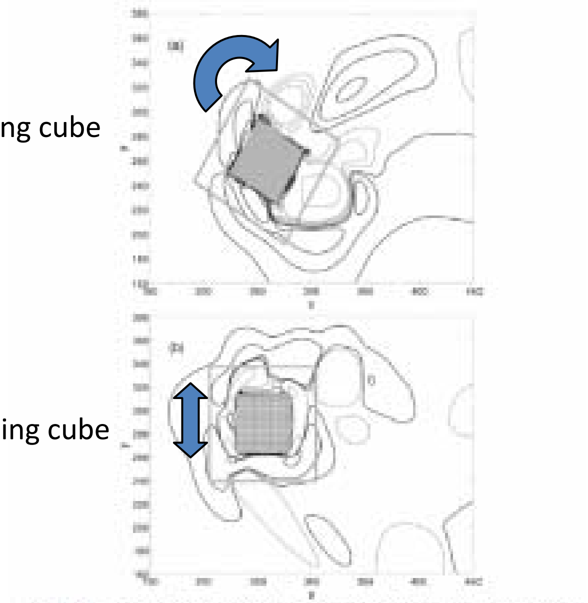
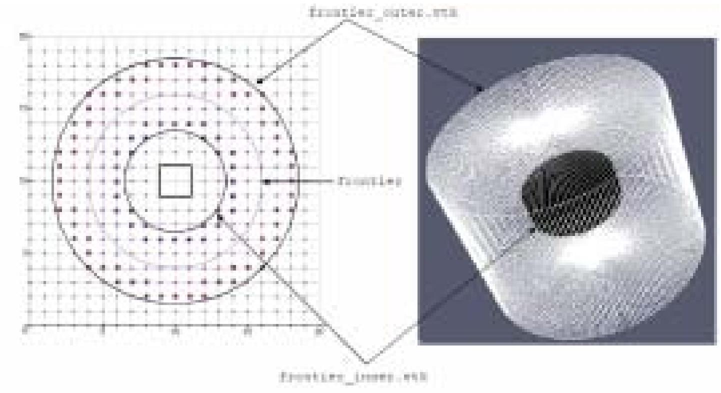
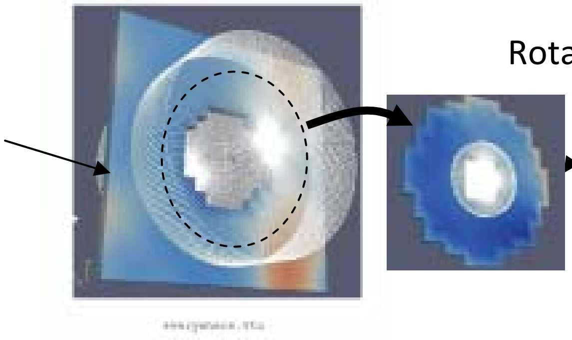


Figure 19: *Isocontours of the Weiss criteria (vorticity in dotted lines) of the flow around a moving two-dimensional square cylinder, immersed in a Poiseuille Flow at Re=70. The laws of motion considered are (a) uniform rotation and (b) transverse harmonic motion.*



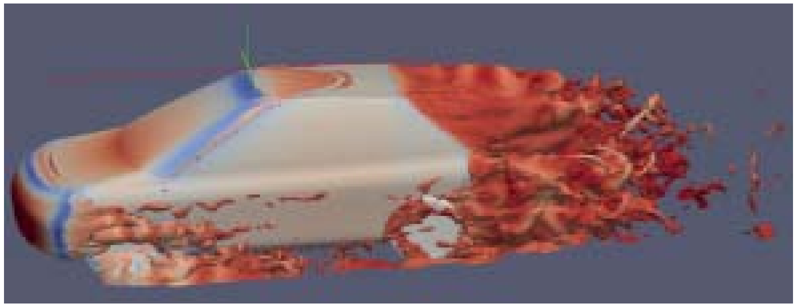
Fixed mesh

Rotating mesh



Conclusions

- New CFD solver based on Lattice Boltzmann method
  - With strong scientific background and careful validation on each application fields
  - Good results on academic cases
  - Satisfactory results on aeroacoustic automotive cases
  - Currently running on several hundreds of CPU



- General CFD simulations can be done
  - DNS (academic cases)
  - LES (with two models : SISM and ADM)
  - WL-LES (Wall Law LES)

- Aeroacoustic is the first application target
  - Wall pressure fluctuation
  - Duct aeroacoustic (under validation)
  - High-lift airfoil noise generation (under validation)
  - Development of advanced acoustic models (time-domain impedance, porous materials,…)

- LaBS will be commercially available in 2013
  - Distributed by CS
  - Offer will comprise GUI / solver license and advanced support
  - CPU-on-Demand solution
  - License will include access to the open source scientific module that contains all physical models. Advanced users will be able to integrate their own LBM / turbulence /… models.