Computational Fluid Dynamics for 3D flow computation, flow control and biological flows

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Lagrangian methods in CFD : Vortex-in-Cell methods

Velocity-Vorticity formulation of Navier-Stokes equations

Curl of Navier-Stokes equations
for an incompressible flow of constant density :

$$\frac{\partial \omega}{\partial t} + u \cdot \nabla \omega - \omega \cdot \nabla u - \nu \mathrm{div}(\mathbf{L} \nabla \omega) = 0,$$

u is the velocity, $\omega = \mathrm{curl} u$ is the vorticity,
$\mathrm{div} u = 0$ in the fluid, $u = 0$ on boundaries
for isotropic flows ($\mathbf{L} \equiv \mathbf{Id}$) or anisotropic flows

$$\Downarrow$$

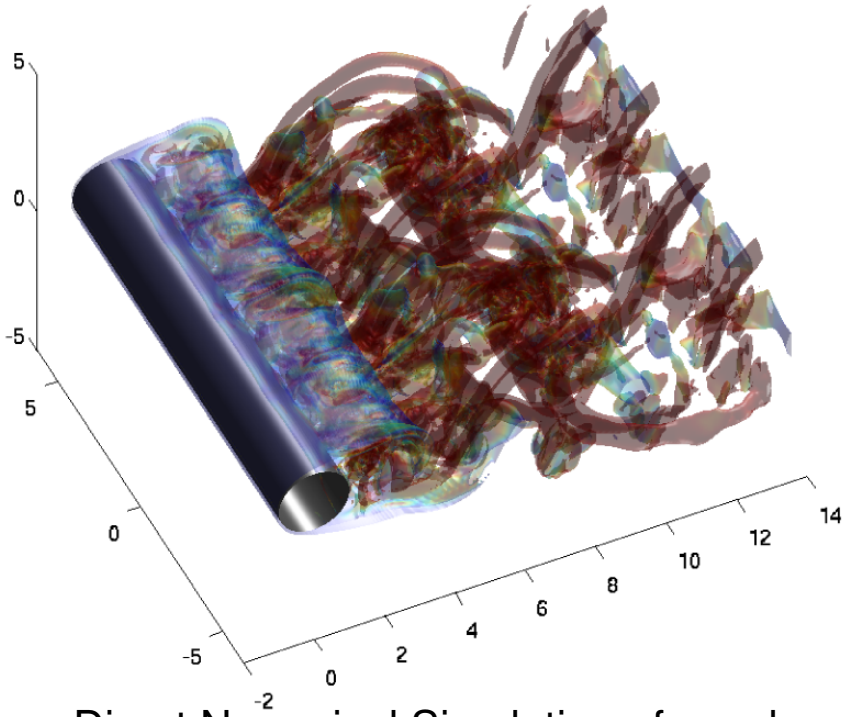
Lagrangian description on vorticity ω
exploiting relations between velocity, vorticity and stream in grids
«Vortex-in-Cell» methods

Main features of Vortex-in-Cell methods

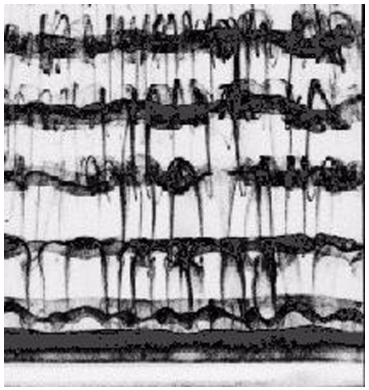
- No transport CFL, highly stable
- Pressure vanishes, as well as its boundary conditions
- Coupling between Lagrangian (particles of fluid) and Eulerian (grid) schemes

Schemes well-suited for computation of non-stationnary large 3D flows

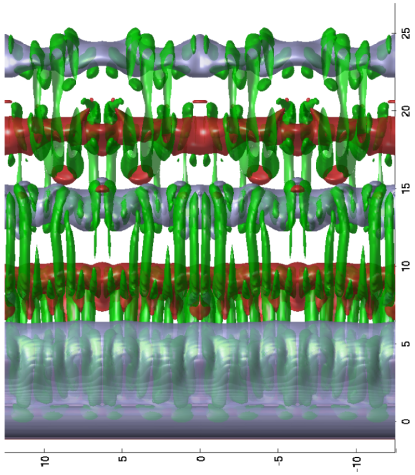
Direct Numerical Simulation of wakes



Direct Numerical Simulation of a wake at Reynolds number $Re = 1000$

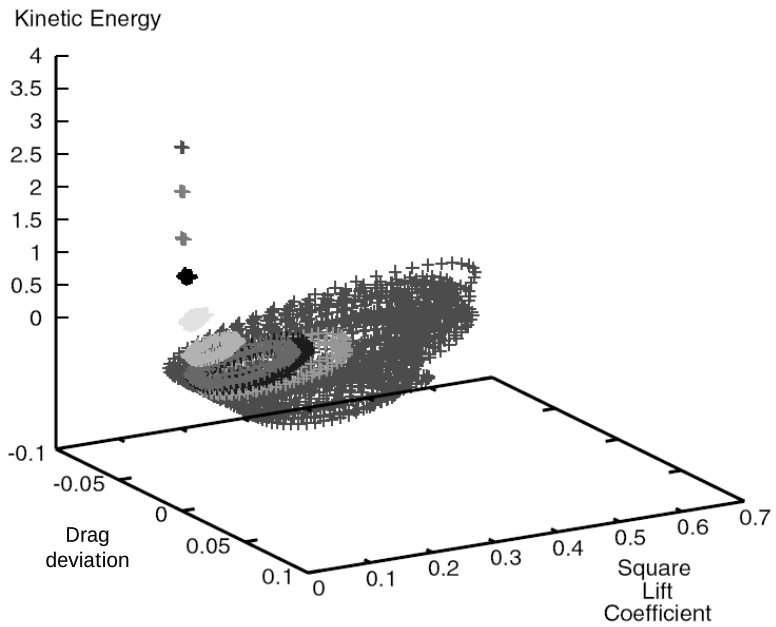


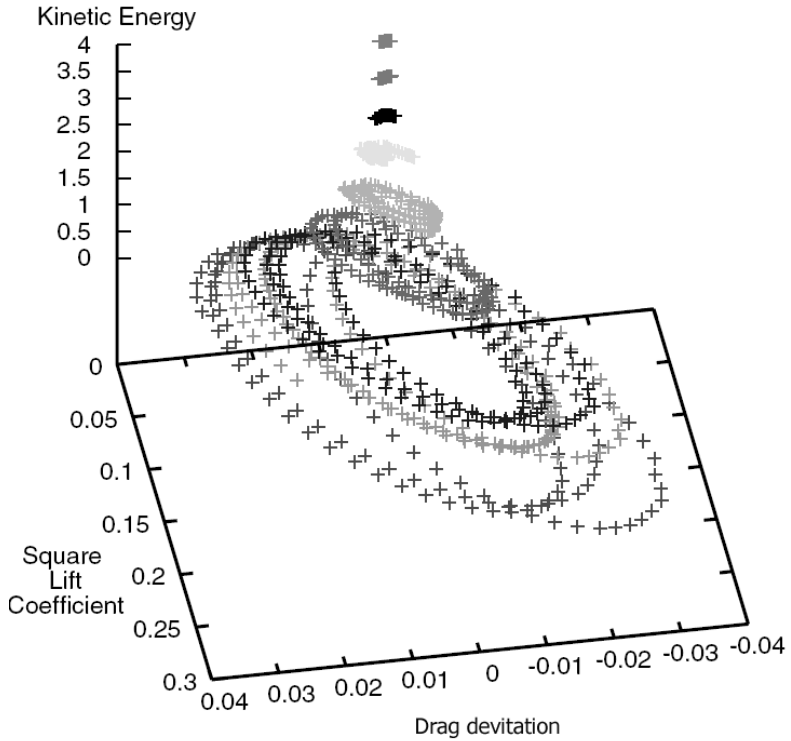
C. H. K. Williamson,
J. Fluid Mech. 328 (1996)



Production of vorticity at walls using integral methods :
P. Poncet, SIAM J. Numer. Anal. 45(6), p. 2259–2297 (2007)

Control of Vortex-Induced-Vibration with tangential actuators

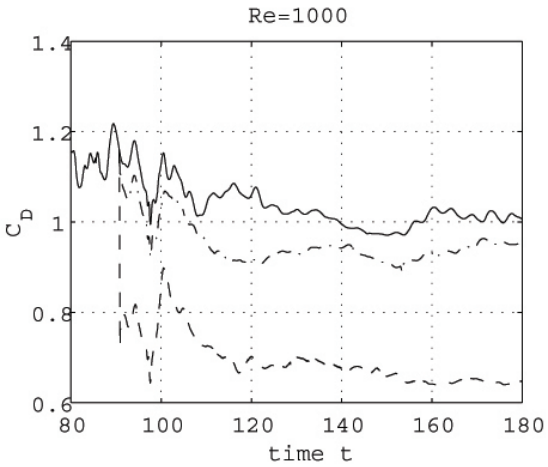




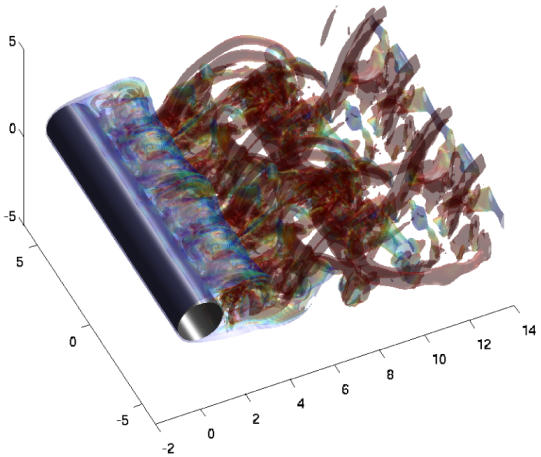
P. Poncet & P. Koumoutsakos, *Optimization of vortex shedding in 3D wakes using belt actuators*, Intl. J. Offshore Polar Eng. 15 (1), pp. 7-14 (2005)

Full 3D control of wakes

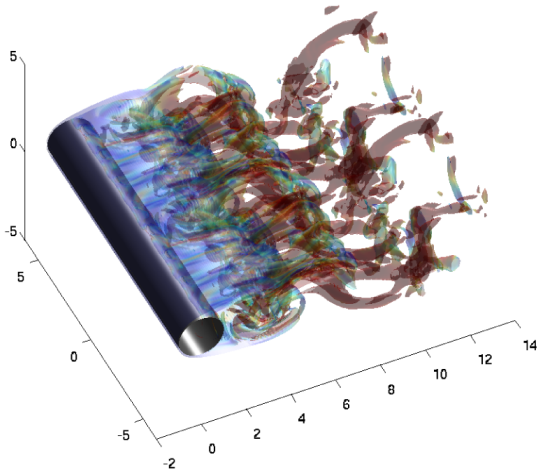
Drag reduction



Without control, Re=1000

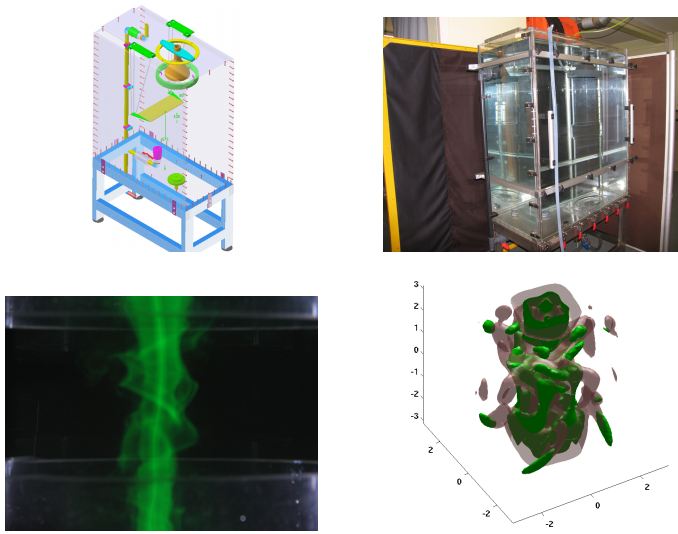


With control, Re=1000

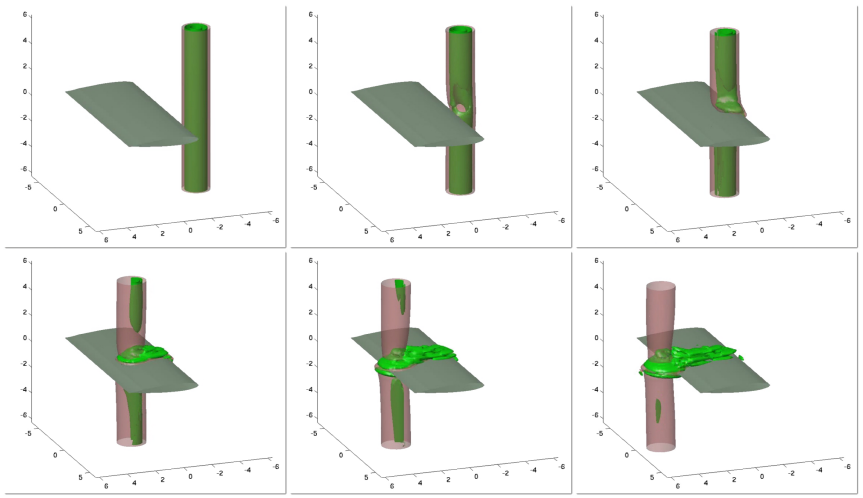


P. Poncet, R. Hildebrand, G-H. Cottet & P. Koumoutsakos, *Spatially distributed control for optimal drag reduction in cylinder wakes*, J. Fluid Mech. 599, pp. 111-120 (2008).

Column-vortex dynamics



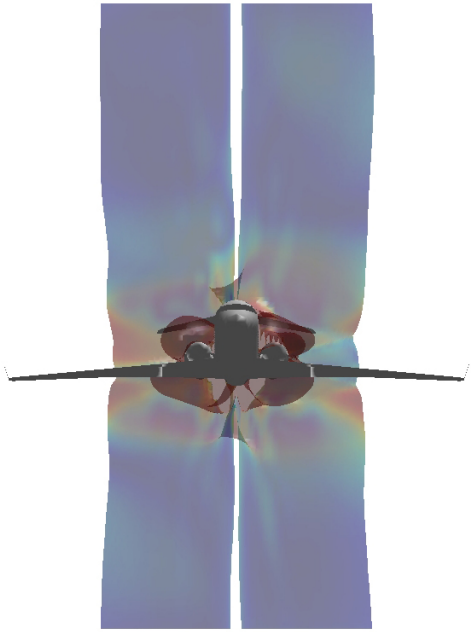
Comparison between experiments and numerical simulations

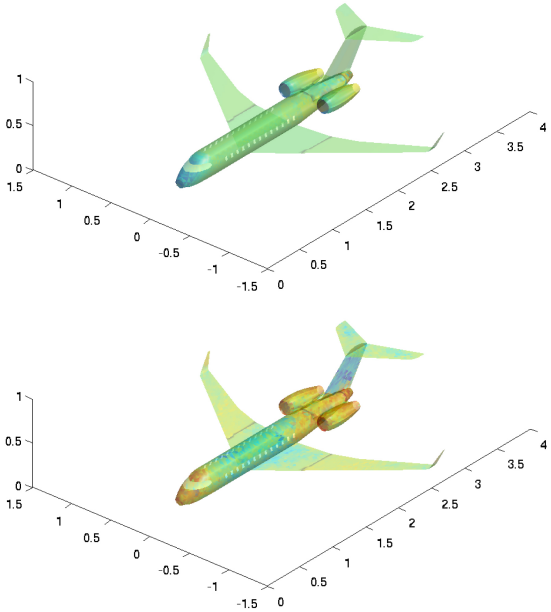


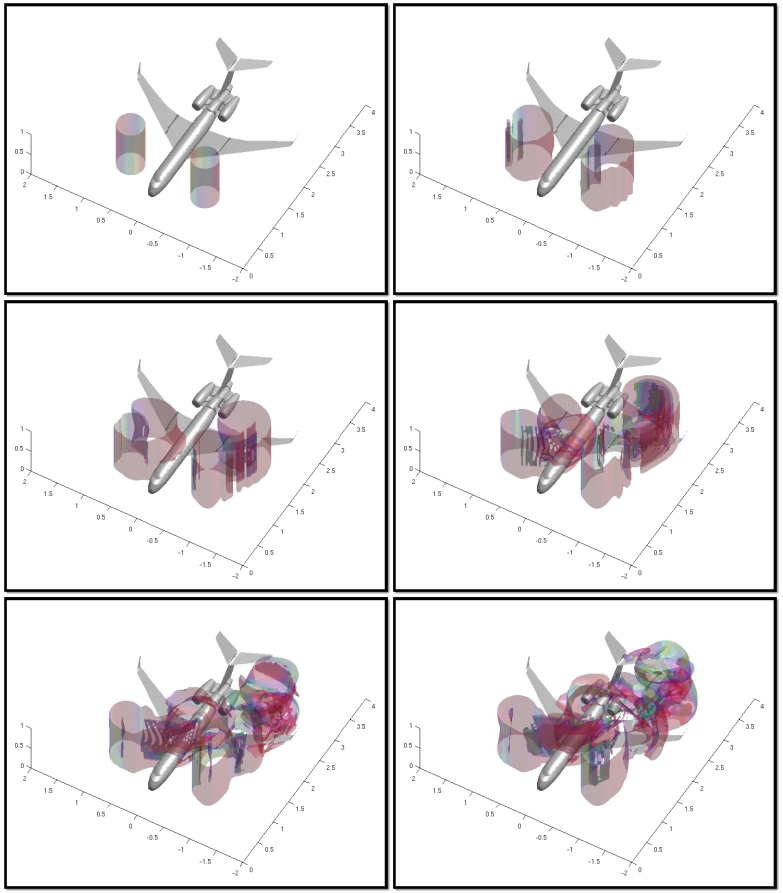
Interaction with a NACA 0012 airfoil

Collaboration with A. Giovannini and P. Brancher (IMFT, Toulouse, France)

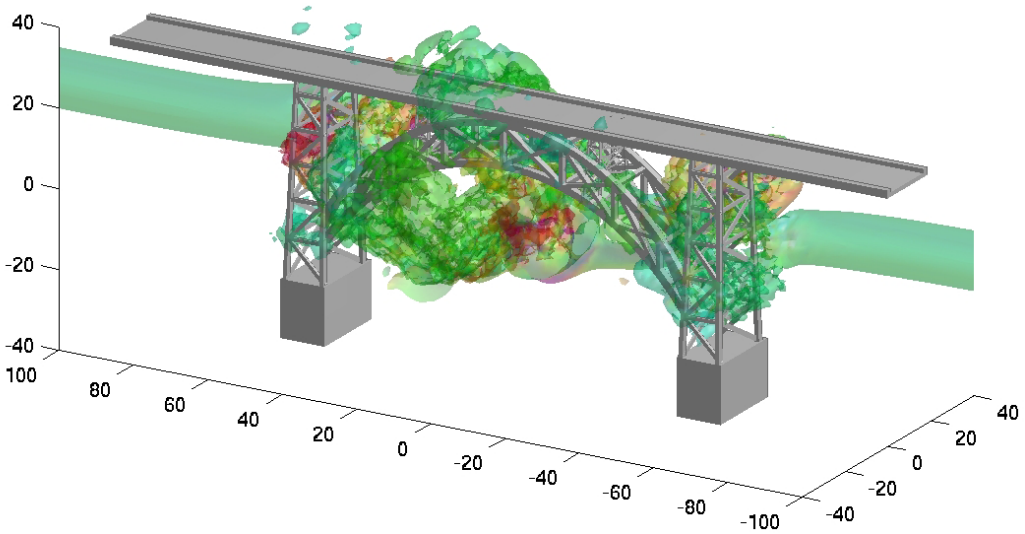
Aircraft Geometry



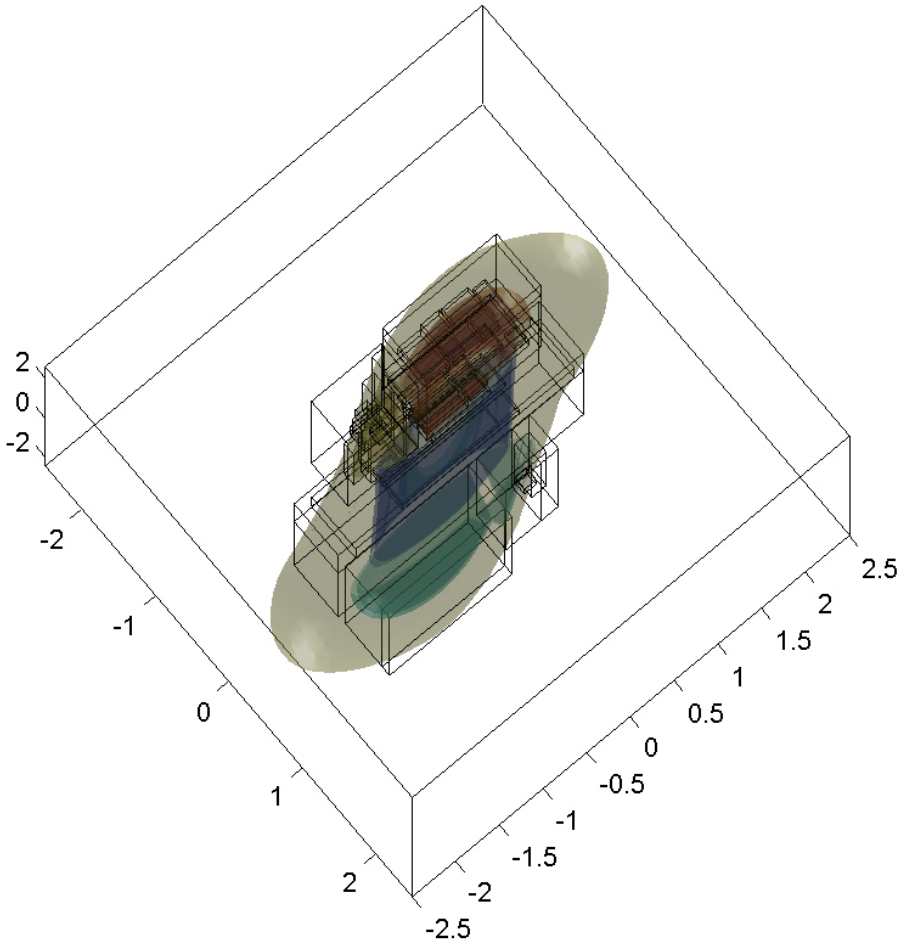


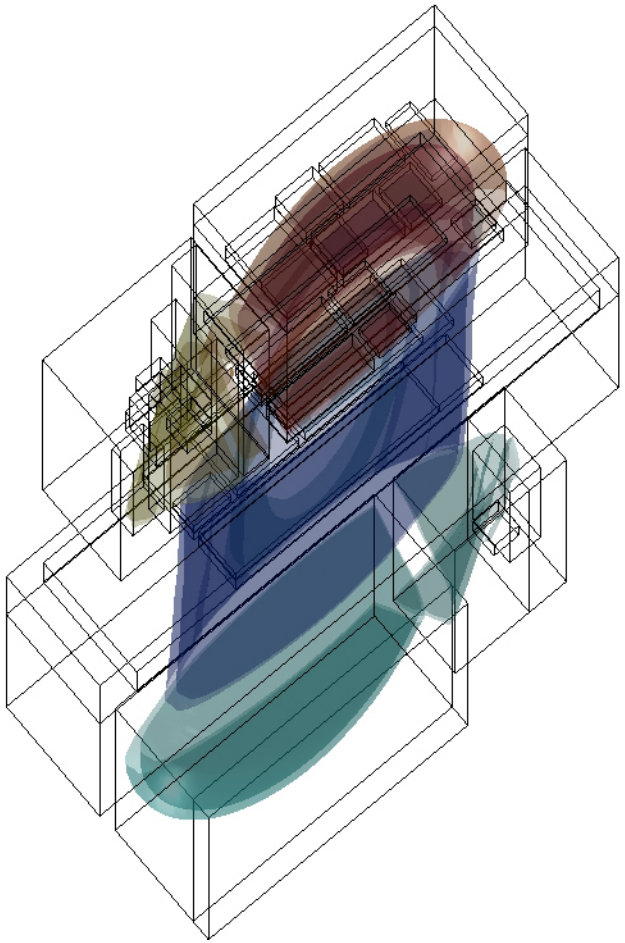


Vortex interaction with hollow geometry

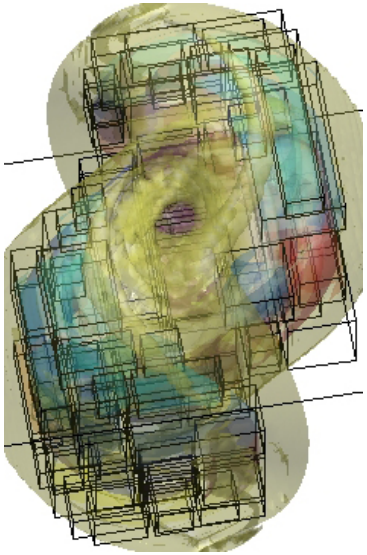


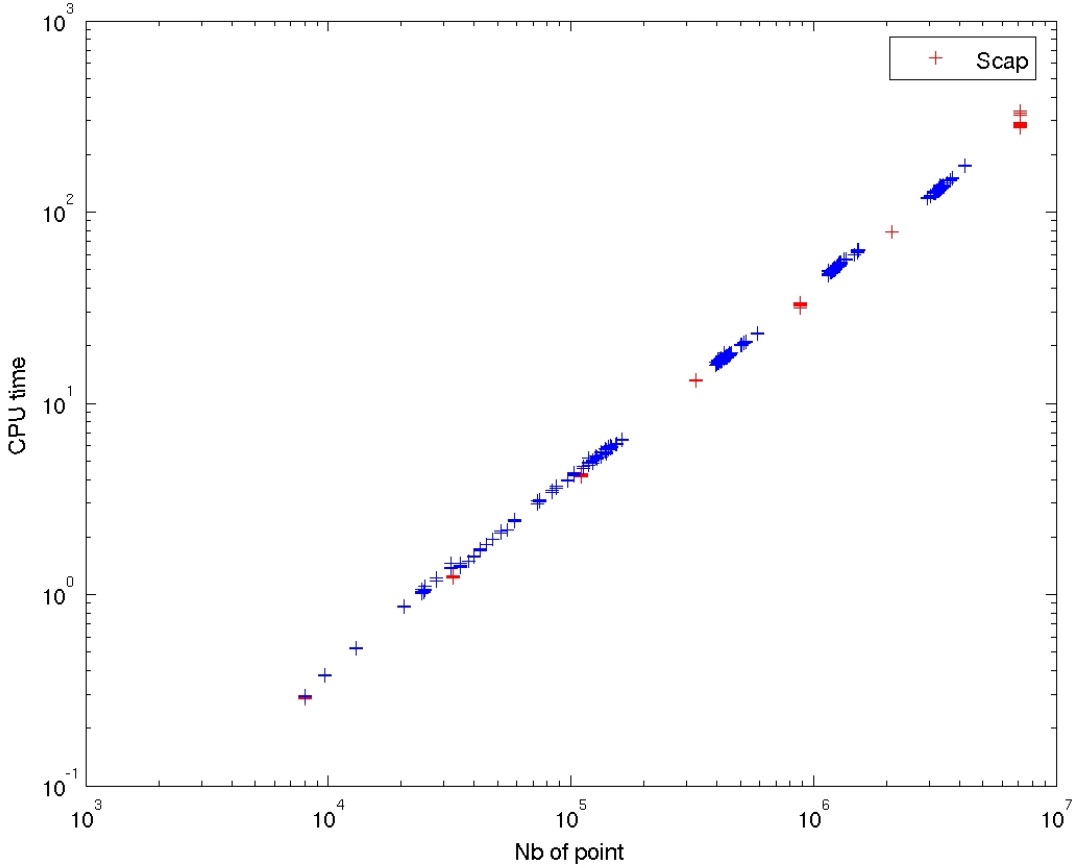
3D multi-scale computing, 3 levels





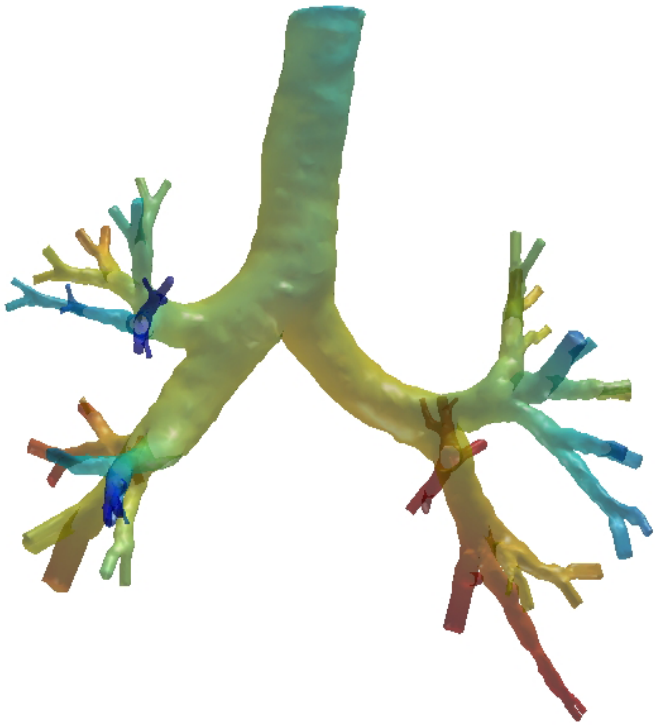
Log-Linear efficiency, CPU time scaling as $\mathcal{O}(n\log n)$

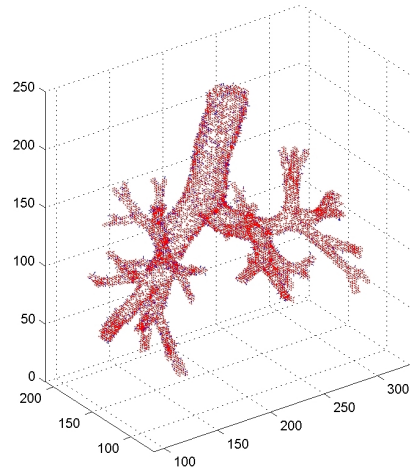


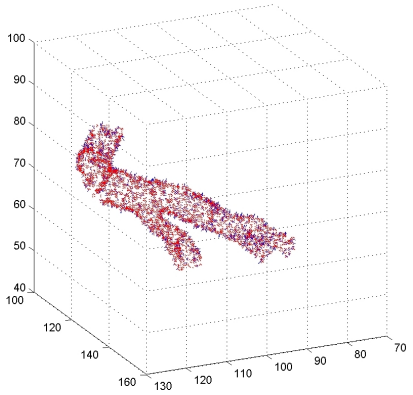


Work done with M. El Ossmani (Post-Doc) – ANR Project "COMMA"

Air transport in lungs

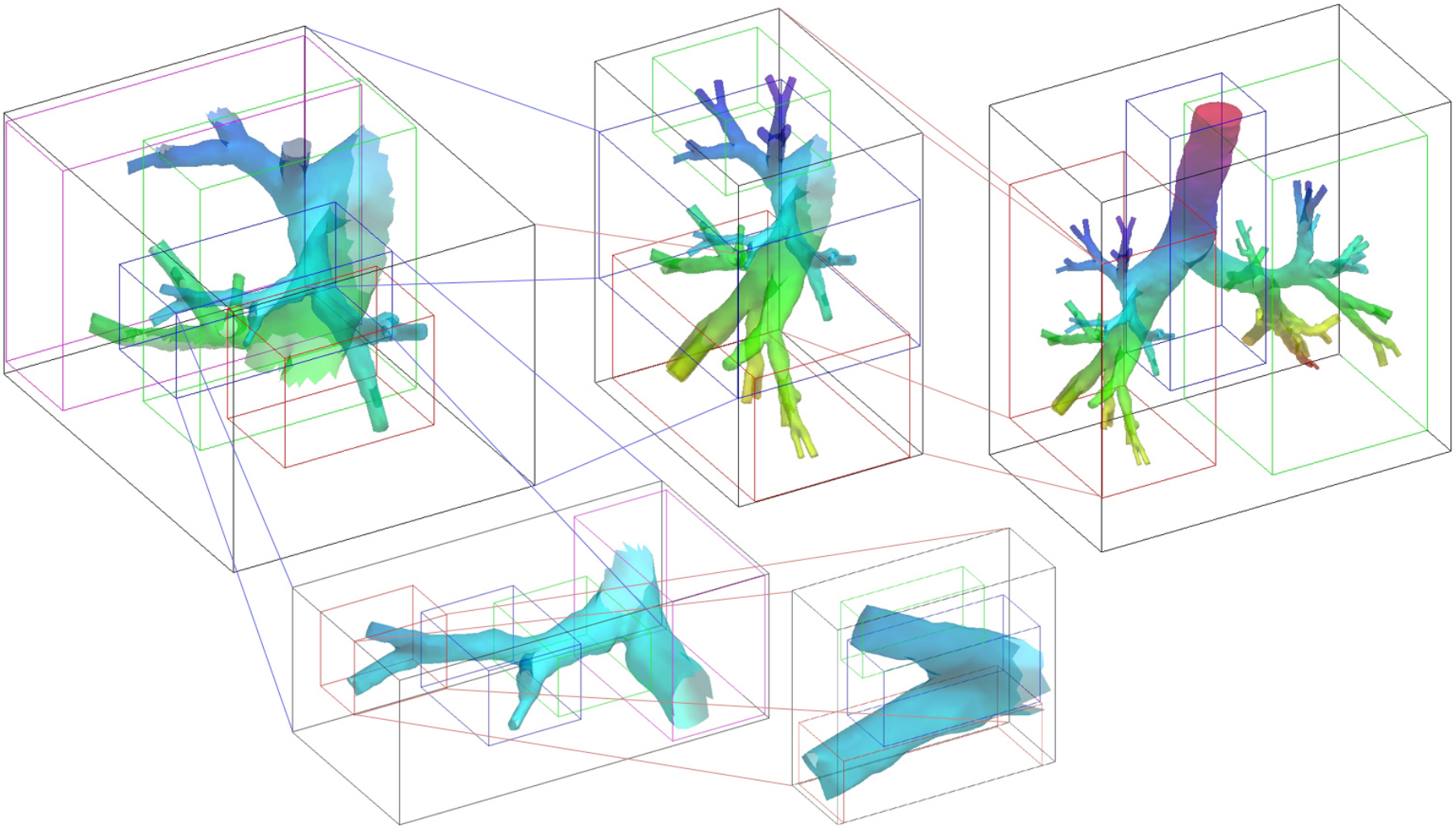




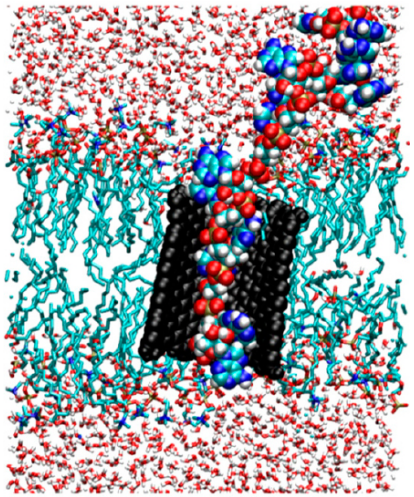


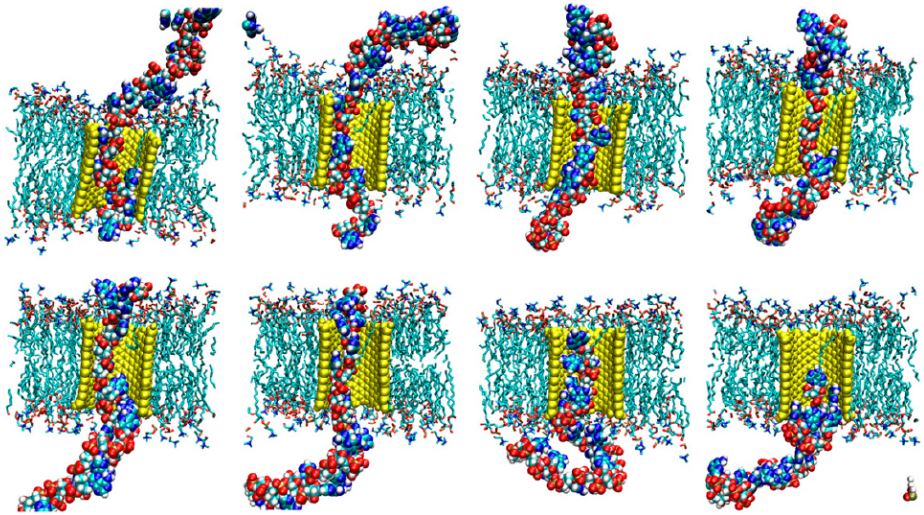
▷ Multi-scale computations required for local or global flow

Air transport in lungs : Multi-scale computations required



Initial motivation for going toward slip flows





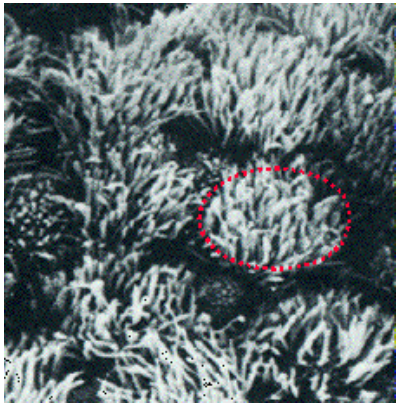
ARN through a bi-lipidic membrane – *Zimmerli & Koumoutsakos*

Navier conditions on tangential components

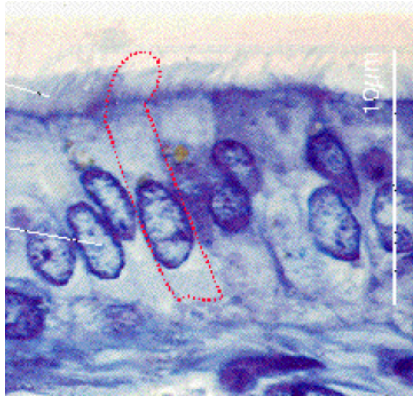
$$u = \lambda \frac{\partial u}{\partial n}, \ \lambda \text{ is a } \textit{slip length}$$

▷ Hydrophobic flows (Chemical potential and/or rarefaction), Roughness, Wall turbulence, Material alteration (Teflon, Nanoturfs, ...), thin gaseous or liquid films

Navier conditions and epithelium



Epithelium cells



Side view

Pseudo Navier conditions

$$u = \lambda \frac{\partial u_{gaz}}{\partial n} + u_F, \text{ with } \lambda = h\, c^{\varepsilon}\, \frac{\mu_{gaz}}{\mu_{liq}}$$

Homogenization and Navier conditions $\longrightarrow$ air dynamics for deep lung computations

Viscous film of mucus with complex interface (two-fluid flow)
$\longrightarrow$ investigate real air dynamics and mucus motion

Futur work and expectations

- On-going project COMMA : Multi-scale vortex flow in complex geometries
- Some perspectives in blending together Vortex-in-Cell methods, grid based methods and Finite-Element-Methods

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- What are the problems in health science, for which developments in flow simulation are the most important ?
- Development strategy and goals of LifeV ?

- Massive parallelisation of multi-scale VIC computing (some implementation and CPU dispatching techniques required before)
- Also involving super-computing : use of virtual reality for flow visualisation