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Direct Forcing methods in Trio_U theory and applications

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DE LA RECHERCHE À L'INDUSTRIE



Direct Forcing methods in Trio_U: theory and applications

Trio_U Meeting | MICHEL BELLIARD

joint work with CLARISSE FOURNIER,
YANNICK GORSSE, CLÉMENT INTROINI,
BENOIT MATHIEU and BÉATRICE ZOPÉ

CEA/DEN

28/01/2015

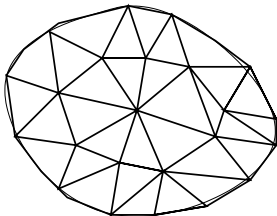
Trio_U Meeting
INSTN, Saclay

- Introduction
- Theoretical developments
- Numerical applications
- Conclusions and Perspectives

Introduction

Complex flow regimes combined with time-varying geometries

- Fluid-Structure Interactions in the nuclear components
 - ★ Flow-induced **vibrations** → possible fuel-rod or U-tube **damages**
 - ★ **Fast** FSI computations with **large deformations**
- Vitrification process for the storage of radioactive wastes
 - ★ Multiphase multicomponent flow at high temperature (gas bubbles, molten glass)
 - ★ Static (vessel structure, measuring apparatus), **moving** (mechanical stirrer) **bodies**



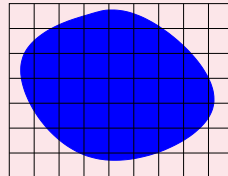
Complex flow regimes combined with time-varying geometries

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Fictitious Domain approach

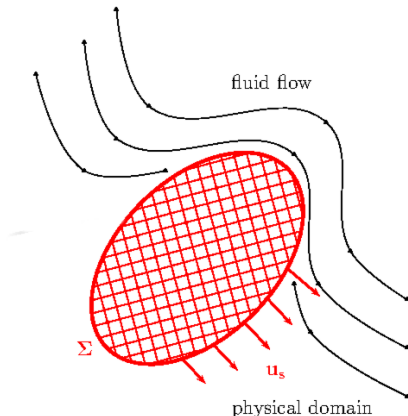
Pioneer's work ([Saul'ev 1963])

- original domain **embedded** in a geometrically bigger and simply-shaped domain : **fictitious domain**
- **computat. domain** = fictitious domain
- **Cartesian mesh** ⇒ fast linear solvers, good numerical properties, easy multiresolution techniques



Fluid governing equations

$$\begin{cases} \frac{\partial \underline{u}}{\partial t} + \nabla \cdot (\underline{u} \otimes \underline{u}) + \frac{1}{\rho} \nabla p - \nu \nabla^2 \underline{u} = \underline{g} & \text{and } \nabla \cdot \underline{u} = 0 \text{ in } \Omega_F \\ \underline{u} = \underline{u}_D \text{ on } \partial\Omega_F \end{cases}$$



Fluid governing equations

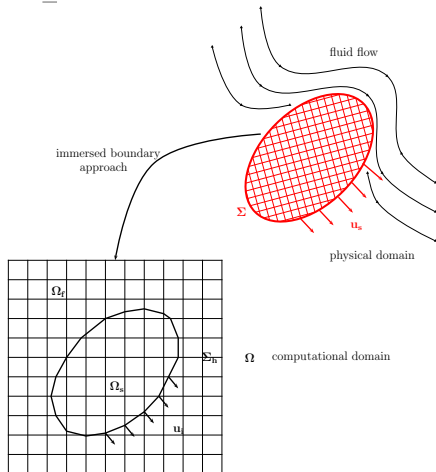
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IBM - DF

$$\begin{aligned} \frac{\underline{u}^* - \underline{u}^n}{\Delta t} + \nabla \cdot (\underline{u}^n \otimes \underline{u}^n) \\ + \frac{1}{\rho} \nabla p^{n+1} - \nu \nabla^2 \underline{u}^n = \underline{g} \text{ in } \Omega \\ \tilde{\underline{u}} = \underline{u}^* + \Delta t \underline{F}_{DF} \end{aligned}$$

$$\underline{F}_{DF} = \chi_m \frac{\underline{u}_i - \underline{u}^*}{\Delta t} \text{ in } \Omega$$

$$\chi_m(\underline{x}) = \begin{cases} 1 & \text{for } \underline{x} \in \Omega_f^m \\ 0 & \text{otherwise.} \end{cases}$$

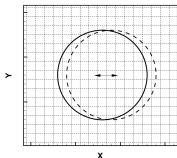


A test case from Seo & Mittal, JCP 230 (2011)

$$x_c(t) = x_c(0) + X_0(1 - \cos(2\pi f_0 t))$$

$$y_c(t) = y_c(0)$$

- Fluid at rest
- Drag coefficient $C_T = C_P + C_V$
- $$C_{DF} = \frac{\iint\int_{\Omega_S} \rho \underline{F}_{DF} \cdot \underline{e}_x d\Omega}{F_{ref} \cdot \underline{e}_x}$$

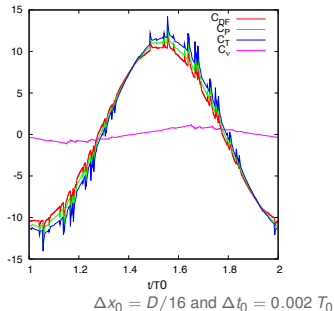
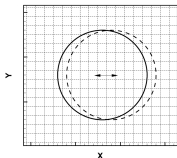


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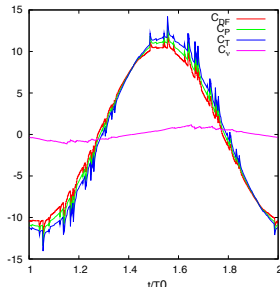
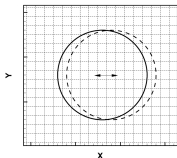
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$$\Delta x_0 = D/16 \text{ and } \Delta t_0 = 0.002 T_0$$

Forcing term is discontinuous in time . . .

$$\int_{\Omega_{s,h}^{n+1}} \underline{F}_{DF}^{n+1} d\Omega - \int_{\Omega_{s,h}^n} \underline{F}_{DF}^n d\Omega = \mathcal{O}(1) + \mathcal{O}(\Delta x) + \mathcal{O}\left(\frac{\Delta x^{2*}}{\Delta t}\right) \quad * : 3 \text{ for the linear model}$$

Theoretical developments

- A combination of the Direct Forcing method [Mohd-Yusof, *CTR An. R. Briefs*, 1997] and L^2 -penalty methods [Angot *et al.*, *Num. Math.*, 1999]

The incompressible N-S equations with a penalized forcing term

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) + \nabla P - \nu \nabla^2 \mathbf{u} = \mathbf{F} \quad \text{and} \quad \nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega$$

where $\mathbf{F} = \frac{\alpha \chi_s}{\eta} (\mathbf{u}_i - \mathbf{u})$ with $\alpha > 0$, $0 < \eta \ll 1$ (here, $\eta = 10^{-12}$) and $\chi_s \rightarrow [0, 1]$

- \mathbf{u}_i depending on \mathbf{u}_s and \mathbf{u} following the requested accuracy
- \mathbf{F} is only applied on Cartesian nodes near/inside the immersed boundary ($\chi_s > 0$)

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- A consistent fractional step method [Ikeno & Kajishima, *JCP*, 2007]

(prediction)
$$\frac{\tilde{\mathbf{u}} - \mathbf{u}^n}{\Delta t} + \nabla_h \cdot (\mathbf{u}^n \otimes \mathbf{u}^n) - \nu \nabla_h^2 \tilde{\mathbf{u}} = \frac{\chi_s}{\eta \Delta t} (\mathbf{u}_i^{n+1} - \tilde{\mathbf{u}}) \quad \text{in } \Omega \quad \text{with } \alpha = 1/\Delta t$$

↪ At this stage, IBCs are only satisfied by the provisional velocity $\tilde{\mathbf{u}}$

(correction)
$$\frac{\mathbf{u}^{n+1} - \tilde{\mathbf{u}}}{\Delta t} + \nabla_h P^{n+1} = \frac{\chi_s}{\eta \Delta t} (\tilde{\mathbf{u}} - \mathbf{u}^{n+1}) \quad \text{in } \Omega$$

↪ At the end of the projection stage, IBCs are also satisfied by the new velocity \mathbf{u}^{n+1}

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(correction)
$$\check{\rho} \frac{\mathbf{u}^{n+1} - \tilde{\mathbf{u}}}{\Delta t} = -\nabla_h P^{n+1} \quad \text{in } \Omega \quad \text{where } \check{\rho} = \left(1 + \frac{\chi_s}{\eta}\right) = \begin{cases} 1 & \text{(fluid)} \\ 1 + 1/\eta & \text{(solid)} \end{cases}$$

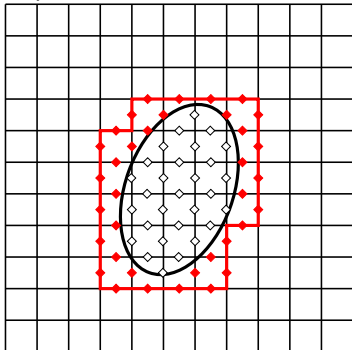
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↪ Homogeneous Neumann BCs for P are naturally enforced on obstacles ($\check{\rho}^{-1} \sim \mathcal{O}(\eta)$)

Base scheme

- $\underline{u}_{\text{base}}(\underline{x}) := \underline{u}_S(\underline{x})$ if $d(\underline{x}) \geq 0$ \diamond
- $d(\underline{x})$ signed distance to Σ_h (> 0 in Ω_S)

$$\Omega_j^{\text{base}} = \{\diamond\}$$



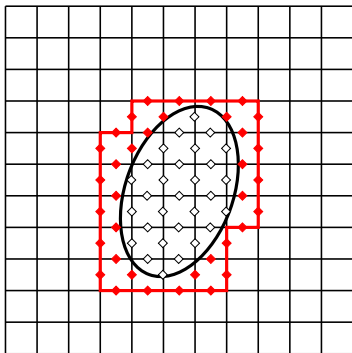
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$$\Omega_I^{\text{linear}} = \{\diamond, \blacklozenge\}$$

Linear interpolation scheme

$$\underline{u}_{\text{linear}}(\underline{x}) := \begin{cases} \underline{u}_{\text{lin_int}}(\underline{x}) & \text{if } -\Delta x \leq d(\underline{x}) < 0 \quad \blacklozenge \\ \underline{u}_S(\underline{x}) & \text{if } d(\underline{x}) \geq 0 \quad \diamond \end{cases}$$



Base scheme

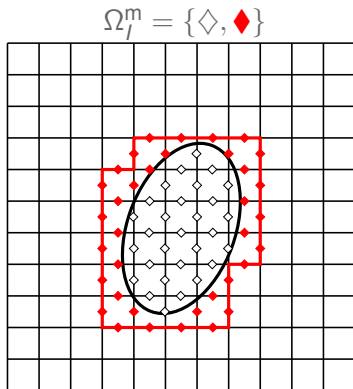
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But possible other choices (higher order schemes, extrapolations, ...)

$$\underline{u}_m(\underline{x}) := \begin{cases} \underline{u}_{\text{ho_int}}(\underline{x}) & \text{if } -\Delta x \leq d(\underline{x}) < 0 \quad \blacklozenge \\ \underline{u}_{\text{ho_extra}}(\underline{x}) & \text{if } d(\underline{x}) \geq 0 \quad \blacklozenge \end{cases}$$



In literature ...

- Volume-weighted model : Kajishima & al., *IJ Heat and Fluid Flow* 23 (2002)
- Differentially interpolated DF : Chiu & al., *JCP* 229 (2010)
- PDE/interpolation hybrid formulation : Luo & al., *Comp. & Fluids* 56 (2012)

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Regularization of \underline{u}_j (Belliard & al. *in prep.*)

$$\begin{cases} \underline{u}_j & = \xi_m \underline{u}_m + (1 - \xi_m) \underline{u}^* \\ \underline{F}_{RG} & = \frac{\underline{u}_j - \underline{u}^*}{\Delta t} \end{cases}$$

$0 \leq \xi_m(\underline{x}) \leq 1$: regular function of $d(\underline{x})$

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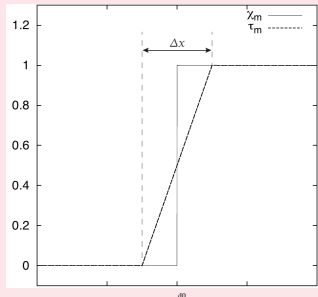
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■ An example ...

$$\xi_m(\underline{x}) = \frac{\Delta x + 2[d(\underline{x}) - d_0^m]}{2\Delta x} \equiv \tau_m(\underline{x})$$



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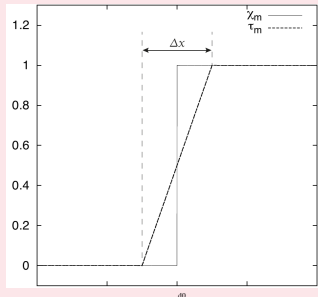
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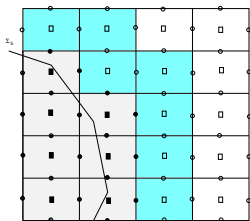
$$\xi_m(\underline{x}) = \frac{\Delta x + 2[d(\underline{x}) - d_0^m]}{2\Delta x} \equiv \tau_m(\underline{x})$$

■ And also regul. hybrid PDF/DF method ...



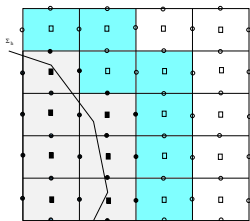
- The heat equation with a penalized forcing term

$$\begin{aligned}
 \partial_t T &= \nabla \left(\frac{\lambda(T)}{\rho_0 C_{P0}} \vec{\nabla} T \right) \\
 &+ (1 - \chi_s) \frac{Q}{\rho_0 C_{P0}} \\
 &- (1 - \chi_s) \vec{V} \cdot \vec{\nabla} T + \frac{\chi_s}{\eta} (T_i - T)
 \end{aligned}$$



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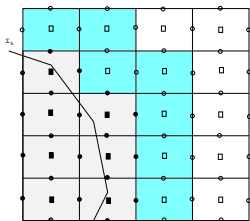


- A fractional semi-implicit time scheme

$$\begin{cases} \frac{T^* - T^n}{\delta t} - \nabla \left(\frac{\lambda(T^n)}{\rho_0 C_{P0}} \vec{\nabla} T^* \right) &= (1 - \chi_s) \frac{Q}{\rho_0 C_{P0}} - (1 - \chi_s) \vec{V}^n \cdot \vec{\nabla} T^n \\ \frac{T^{n+1} - T^*}{\delta t} - \frac{\chi_s}{\eta} (T_i - T^{n+1}) &= 0 \end{cases}$$

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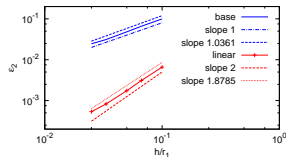
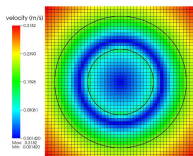
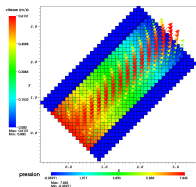
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- Models :

- Base : $T_i = T_s$
- Weighted : $T_i = \tau_s T_s + (1 - \tau_s) \langle T_{neig.} \rangle$ with $\tau_s|_K = vol_s|_K / vol_K$
- Treatment of fresh cells by an averaging process

Numerical applications

■ Poiseuille and Taylor-Couette flows

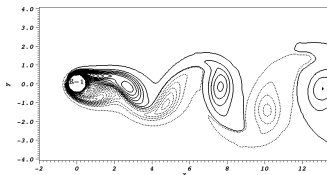


■ Rotating cylinder ($\mathcal{R} = 100$, $D/h \sim 50$)

[Stojković *et al.*, Phys. Fluids, 02]¹

[Kang *et al.*, Phys. Fluids, 99]²

	Present results	Ref.	
		[1]	[2]
C_d	1.12	1.1080	1.0979
C_d'	± 0.11	± 0.0986	± 0.0988
C_l	2.51	2.504	2.4833
C_l'	± 0.37	± 0.3616	± 0.3603
St	0.165	0.1658	0.1650



(solid/dotted lines : neg./pos. contours)

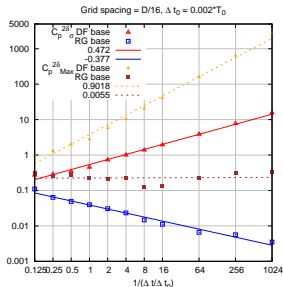
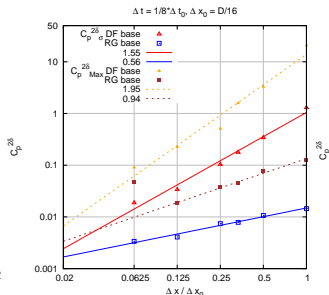
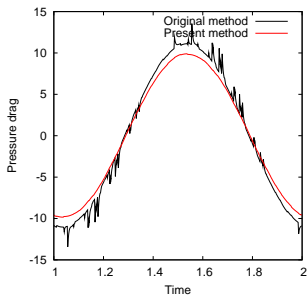
Analysis for the base model ...

$$\begin{aligned}
 \int_{\Omega_{s,h}^{n+1}} \underline{F}_{RDF}^{n+1} d\Omega - \int_{\Omega_{s,h}^n} \underline{F}_{RDF}^n d\Omega &= \underbrace{\mathcal{O}(1) + \mathcal{O}(\Delta t) + \mathcal{O}(\Delta x)}_{K \in \Omega_{s,h}^{n+1} \cap \Omega_{s,h}^n} + \underbrace{\mathcal{O}(\Delta t) + \mathcal{O}(\Delta x)}_{K \in DC} + \underbrace{\mathcal{O}(\Delta t)}_{K \in FC} \\
 &= \mathcal{O}(1) + \mathcal{O}(\Delta t) + \mathcal{O}(\Delta x^*) \quad * : 2 \text{ for the linear model}
 \end{aligned}$$

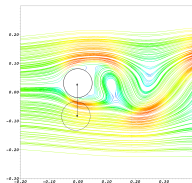
Analysis for the base model ...

$$\int_{\Omega_{s,h}^{n+1}} F_{RDF}^{n+1} d\Omega - \int_{\Omega_{s,h}^n} F_{RDF}^n d\Omega = \underbrace{\mathcal{O}(1) + \mathcal{O}(\Delta t) + \mathcal{O}(\Delta x)}_{K \in \Omega_{s,h}^{n+1} \cap \Omega_{s,h}^n} + \underbrace{\mathcal{O}(\Delta t) + \mathcal{O}(\Delta x)}_{K \in DC} + \underbrace{\mathcal{O}(\Delta t)}_{K \in FC}$$

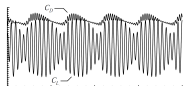
$$= \mathcal{O}(1) + \mathcal{O}(\Delta t) + \mathcal{O}(\Delta x^*) \quad * : 2 \text{ for the linear model}$$



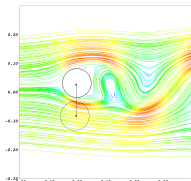
An oscillating cylinder in cross-flow ($Re = 185$, Guilmineau & Queutey, *JFS 16*, 2002)



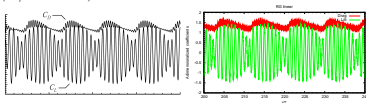
$(D/\Delta x = 25)$



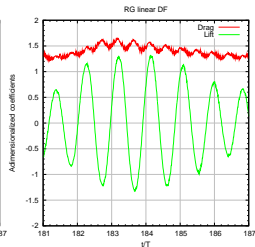
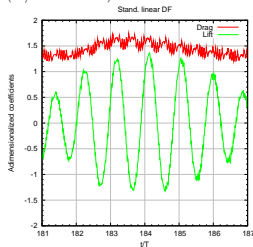
An oscillating cylinder in cross-flow ($Re = 185$, Guilmineau & Queutey, *JFS 16*, 2002)



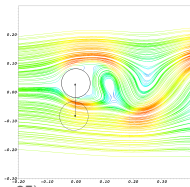
$(D/\Delta x = 25)$



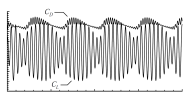
$(D/\Delta x = 12.5)$



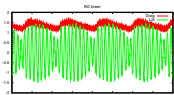
An oscillating cylinder in cross-flow ($Re = 185$, Guilmineau & Queutey, *JFS 16*, 2002)



$(D/\Delta x = 25)$

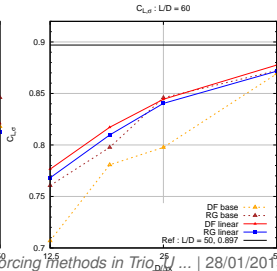
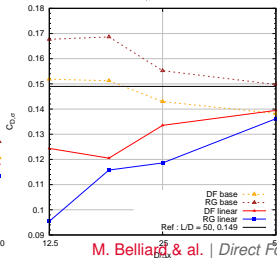
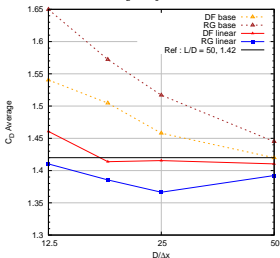
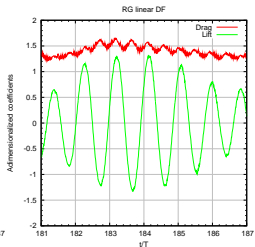
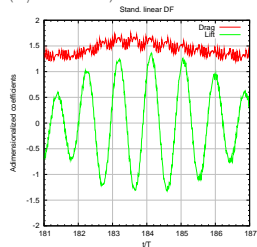


C_D Average : $L/D = 60$

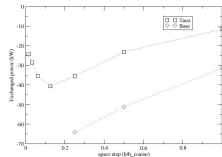


$C_{D,0}$: $L/D = 60$

$(D/\Delta x = 12.5)$

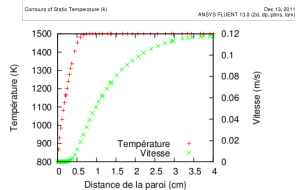
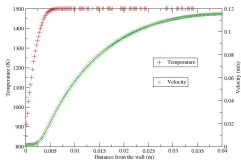
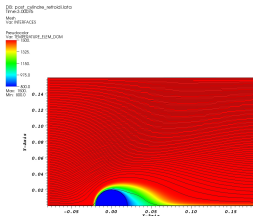
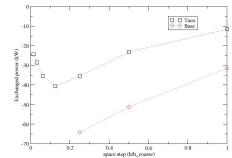


- $\mu(T) \in [1; 10^5]$, $\Lambda(T)$ and Boussinesq approx.
- **Fluent benchmark** simulation
(boundary layer : AMR ; 14,000 faces)
- **Mesh convergence study** (2,400 \rightarrow 10 M cells)



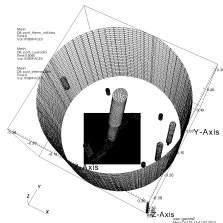
cea 2D molten glass flow over a cold cylinder

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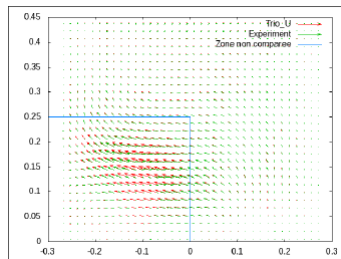
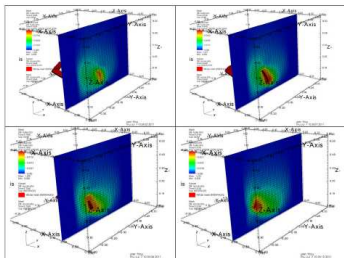
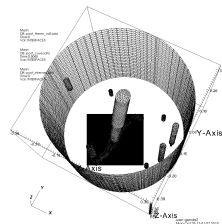
Hydraulic validations of flows induced by a stirrer

- Experimental device filled with viscous oil ($\mathcal{R} \approx 100$) - PIV -
- IBC Lagrangian meshes from CAD
- Regular Eulerian meshes

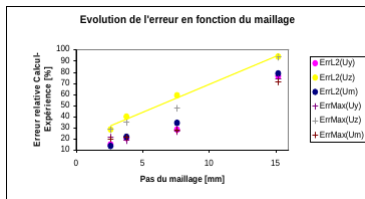
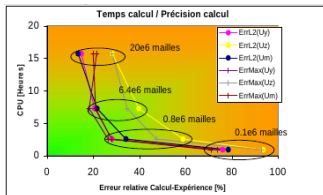


Hydraulic validations of flows induced by a stirrer

- Experimental device filled with viscous oil ($\mathcal{R} \approx 100$) - PIV -
- IBC Lagrangian meshes from CAD
- Regular Eulerian meshes
- Velocity-profile comparisons on a cut-plane and lines
- Fluent body-fitted sliding-mesh simulations (1 M cells with AMR)

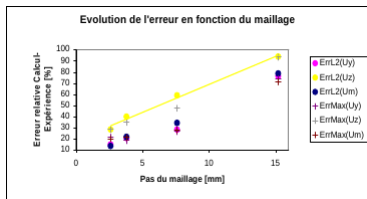
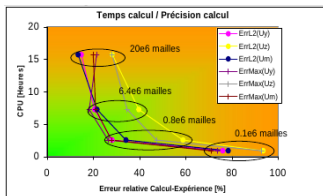


■ **Base model** : mesh convergence study (0.05 → 20 M cells ; 2 → 400 CPUs)



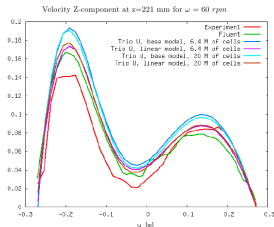
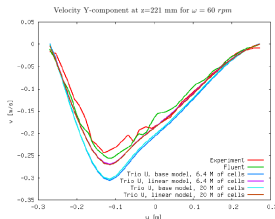
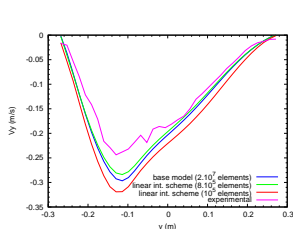
- Experimental rate of convergence about 0.6

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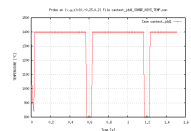
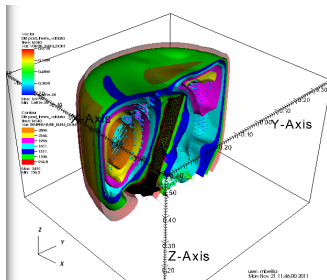
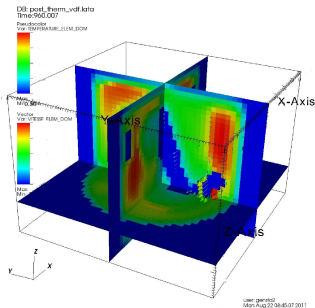
- Experimental rate of convergence about **0.6**

■ **Linear vs base model** : cost ↘ for a given accuracy (1 M cells is quasi-optimal)

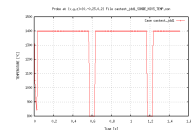
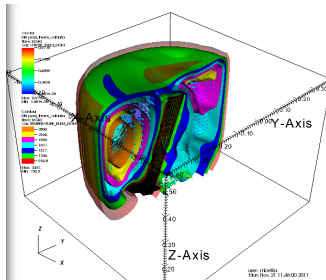
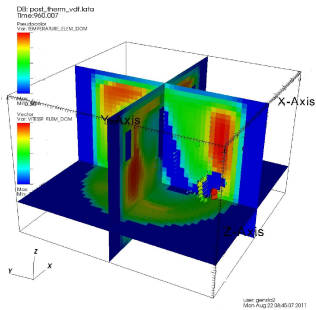


- Experimental rate of convergence about **1.0** for coarse meshes (but, exp. errors...)
- Trio_U results **compare well** with experiment and Fluent ones

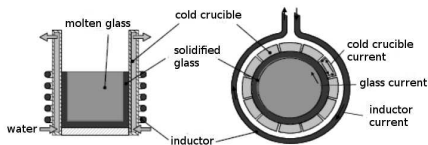
■ Thermal-hydraulic simulations ; $\mu(T) \in [1; 10^5]$, $\Lambda(T)$ and Boussinesq approx., $\mathcal{R} \approx 100$



- Thermal-hydraulic simulations ; $\mu(T) \in [1; 10^5]$, $\Lambda(T)$ and Boussinesq approx., $\mathcal{R} \approx 100$



- Hydraulic bubbling simulations



Conclusions - Perspectives

- Development of a **Penalized Direct Forcing** method
 - Finite Volume approximation with a staggered arrangement of variables
 - ↪ To solve the Navier-Stokes equations on Cartesian grid with penalized forcing term taking into account immersed boundary conditions
 - ↪ To account for the IBCs in the prediction and correction equations
- Development of an original **robust interpolation scheme**
 - ↪ To reconstruct accurately the velocity field near the immersed boundary
- **SFO** analysis & development of **regularized** DF and PDF methods
- **CFD assessment** on Academical test cases ($\mathcal{O}(h^2)$) in L^2 - and L^∞ -norms)
- **Cutting off** the SFO **without altering** physical phenomena nor the space convergence orders
- Numerical **simulations** of the **cold crucible** process
 - ↪ Hydraulic assessment vs experiment and code results
 - ↪ Thermal-hydraulic assessment vs code benchmark
 - ↪ Hydraulic bubbling simulations with IBCs give satisfactory results

- ⇒ Increase of the **validation** basis
- ⇒ Extension of our Penalized Direct Forcing method
 - Energy equation : **linear interpolation** for the **temperature**
 - Including **AMR** ...
 - **Increasing** the **Reynolds** number ...
- ⇒ **FSI** applications for single-phase and two-phase fluids
- ⇒ **Cold crucible** process simulations
 - Bubbling : convergence study and assessment vs experiment

Thank you for your attention ...

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | DEN/DER/SESI b1222 - 13108 Saint-Paul-lez-Durance Cedex
T. +33 (0)4.42.25.70.52 | F. +33 (0)4.42.25.48.58
Établissement public à caractère industriel et commercial | RCS Paris B 775 685 019

Direction de l'Énergie Nucléaire
Département d'Études des Réacteurs
Service d'Études des Systèmes Inno-
vants