

High Reynolds flows DDES over a square rounded cylinder using OpenFOAM

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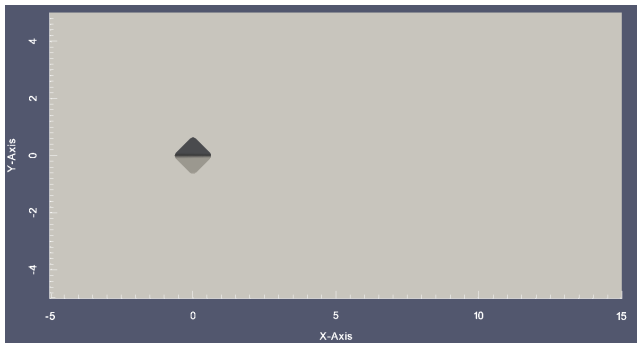
- An international collaborative numerical benchmark following (OMAE2013-10200) carried out at moderate Re ($Re=22000$).
- Flow configurations representative of full scale offshore conditions
- Collaboration between *M2P2/PPRIME/SEAL engineering (Technip Subsidiary)* :
 - dev of advanced methods for turbulent flows over bluff bodies
 - choice of implementing some of them in OpenFOAM as an open source flexible code

THE OBJECTIVES

- 1 Evaluate the numerical tool through a demanding exercise: blind tests at $Re = 10^5$ and $Re = 10^7$ ($Re = \frac{U_\infty L_D}{\nu}$)
- 2 Provide reliable data to describe and understand the physics

THE DOMAIN

- A square column of section D located at the the origin in x, y
- Rounded corners ($r/D = 0.16$, with r the corner radius)
- The physical domain: $[-5D, 15D] \times [-5D, 5D] \times [0, 10D]$
- Heading angle $\alpha = 45^\circ \rightarrow$ renormalization length $L_D = 1.28167D$



THE NUMERICS: *OpenFOAM*

- The native *OpenFOAM* SA-DDES equations are solved using *pimpleFoam* (predictor-corrector algo merging PISO & SIMPLE):
 - use an adaptative time-step with a local constraint $\max(Co) \leq 1.5$. In average $Co \cong 0.1, 0.2$
- A 2^{nd} -order *implicit backward scheme* for the time derivative
- A 2^{nd} -order *centered scheme* for the space derivative
- Except the advection: linear-upwind stabilized transport (LUST) scheme
 - blends a 2^{nd} -order upwind (25%) with a 2^{nd} -order centered scheme (75%) (compromise between stability and dissipation)
- Computations have been run on *72 cores* on AMU computing center over *50000 hours* for about 50 sheddings time.

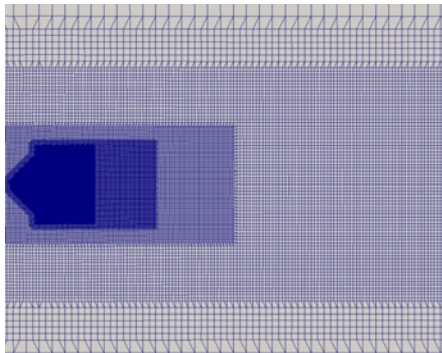
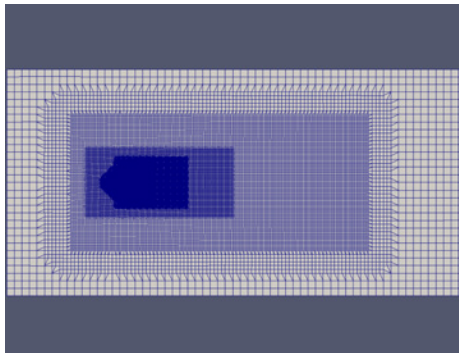
Boundary conditions for the DDES simulation

	U	p	ν_T
Inlet	Fixed ($[1, 0, 0]$)	Zero gradient	Fixed $10^{-5} / 10^{-7}$
Outlet	Zero gradient	Fixed (0)	Zero gradient
Normal	Slip	Zero gradient	Zero gradient
Spanwise	Periodic	Periodic	Periodic
Wall	Fixed ($[0, 0, 0]$)	Zero gradient	Fixed (0) / Spalding law

For ν_T , the first value refers to the simulation for $Re = 10^5$, the second refers to the simulation for $Re = 10^7$.

THE MESH

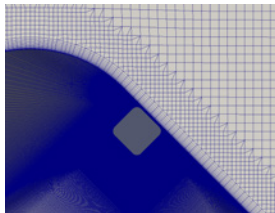
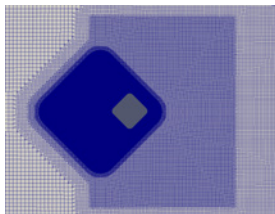
- An unique block structured mesh has been carefully designed : 27.4×10^6 elements made prevalently by hexahedral elements (compromise between accuracy / numerical cost)



THE RESOLUTION AT THE COLUMN

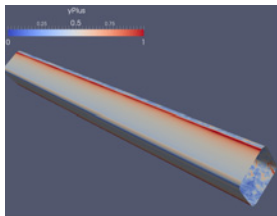
The resolution at the cylinder surface is uniform:

- Normal direction: $\Delta_n = 2.13 \times 10^{-4} D$
 $\rightarrow \Delta_n^+ = 1.2$ ($Re = 10^5$) to
98 ($Re = 10^7$)
- Streamwise direction:
 $\Delta_s = 7.36 \times 10^{-3} D$
 $\rightarrow \Delta_s^+ = 41.5$ ($Re = 10^5$) to
3389 ($Re = 10^7$)
- Spanwise direction :
 $\Delta_z = 1.04 \times 10^{-2} D$
 $\rightarrow \Delta_z^+ = 58.5$ ($Re = 10^5$) to
4777 ($Re = 10^7$)



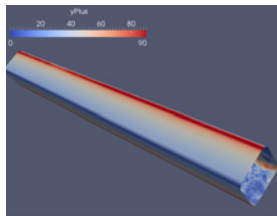
THE RESOLUTION AT THE COLUMN: y^+

$Re = 10^5$

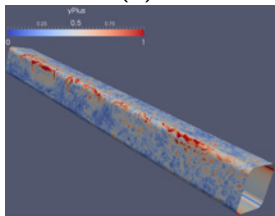


(a)

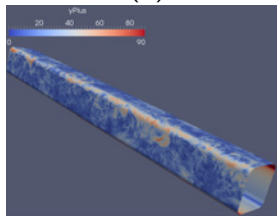
$Re = 10^7$



(b)



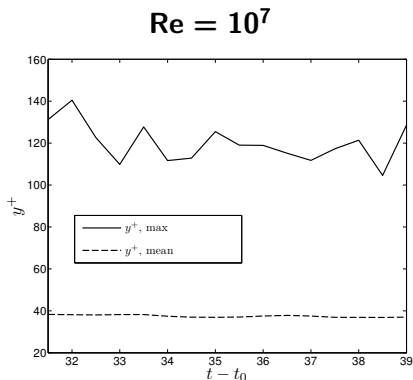
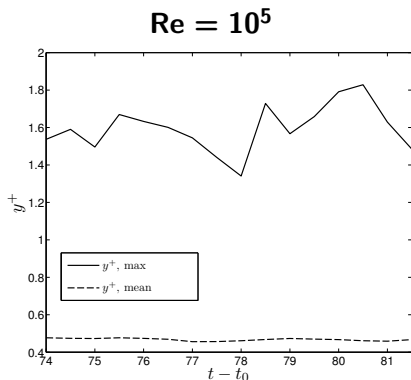
(c)



(d)

Instantaneous isocontours: (a,b) front, (c,d) back.

THE RESOLUTION AT THE COLUMN: y^+



$y_{\text{max}}^+(t)$ and $\langle y^+(t) \rangle$ average on the surface of the cylinder

THE RESOLUTION IN THE NEAR WAKE (*a priori*)

The grid is stretched when going downstream:

Considering the Kolmogorov scale $\eta = Re^{-3/4} \times L_D$

for $Re = 10^5$:

- $\Delta_x = \Delta_y = 37.83 \eta$, $\Delta_z = 75.64 \eta$ for $x \leq 1.1 L_D$
- $\Delta_x = \Delta_y = 75.64 \eta$, $\Delta_z = 151.28 \eta$ for $x \leq 2.37 L_D$
- $\Delta_x = \Delta_y = 151.28 \eta$, $\Delta_z = 302.56 \eta$ for $x \leq 3.91 L_D$

for $Re = 10^7$:

- $\Delta_x = \Delta_y = 1196 \eta$, $\Delta_z = 2392 \eta$ for $x \leq 1.1 L_D$
- $\Delta_x = \Delta_y = 2392 \eta$, $\Delta_z = 4784 \eta$ for $x \leq 2.37 L_D$
- $\Delta_x = \Delta_y = 4784 \eta$, $\Delta_z = 9568 \eta$ for $x \leq 3.91 L_D$

THE RESOLUTION IN THE NEAR WAKE (*a priori*)

The grid is stretched when going downstream:

Considering the large scale structure at separation $L_S = 20 \times Re_{L_D}^{-0.5}$

for $Re = 10^5$:

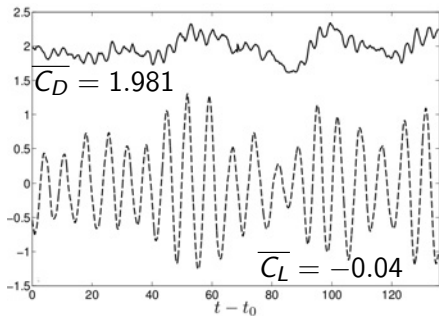
- $\Delta_x = \Delta_y = 0.1724 L_S$, $\Delta_z = 0.3447 L_S$ for $x \leq 1.1 L_D$
- $\Delta_x = \Delta_y = 0.3447 L_S$, $\Delta_z = 0.6894 L_S$ for $x \leq 2.37 L_D$
- $\Delta_x = \Delta_y = 0.6894 L_S$, $\Delta_z = 1.3789 L_S$ for $x \leq 3.91 L_D$

for $Re = 10^7$:

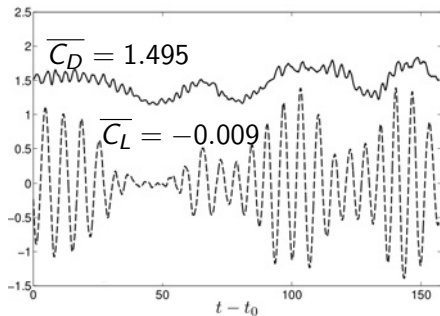
- $\Delta_x = \Delta_y = 1.724 L_S$, $\Delta_z = 3.447 L_S$ for $x \leq 1.1 L_D$
- $\Delta_x = \Delta_y = 3.447 L_S$, $\Delta_z = 6.894 L_S$ for $x \leq 2.37 L_D$
- $\Delta_x = \Delta_y = 6.894 L_S$, $\Delta_z = 13.79 L_S$ for $x \leq 3.91 L_D$

THE DRAG C_D AND THE LIFT C_L COEFFICIENTS

Observed over at least 10 shedding characteristic time:

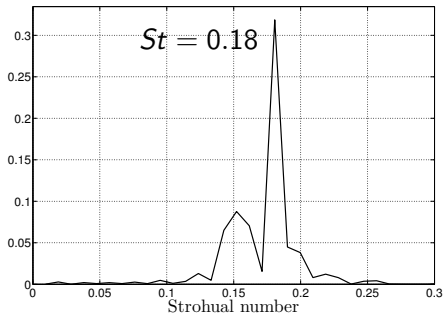


$Re = 10^5$

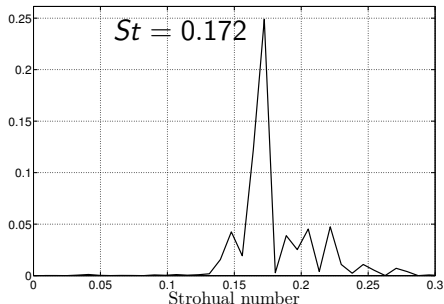


$Re = 10^7$

THE STROUHAL NUMBER



$Re = 10^5$



$Re = 10^7$

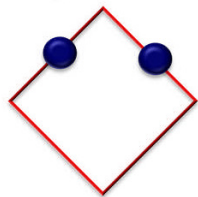
St number based on the lift coefficient

STATISTICS OF THE BULK FLOW MAIN QUANTITIES: NUM/EXPE

	$\overline{C_D}$	C'_D	$\overline{C_L}$	C'_L	St
Re = 10⁵					
Expe	1.77	0.22	0.023	0.44	0.17
DDES	1.981	0.155	-0.04	0.6	0.18
% diff	~ +11	~ -30	~ 100	~ +36	~ +5
Re = 10⁷					
Expe	1.59	0.16	-0.002	0.43	0.19
DDES	1.495	0.175	-0.009	0.576	0.172
% diff	~ -6	~ +11	~ +450	~ +33	~ -9

The convergence error is estimated to be 1 – 2% for the averaged quantities and 3% for the fluctuating quantities, respectively.

STATISTICS OF THE PRESSURE AND RECIRCULATION LENGTH NUM/EXPE



45 deg

Two probes like in experiments at the points (front) $[0.3536; 0.3536; 5]$ and (back) $[0.3536; 0.3536; 5]$

- $C_p = (p - p_\infty)/(0.5 U_\infty^2)$ is calculated using the reference pressure p_∞ at the inlet (max or averaged) for $y = 0, z = 5$.
- The separation angle θ_s is calculated following the direction from the x axis to the y axis.
- The recirculation length L_r is normalized over L_D

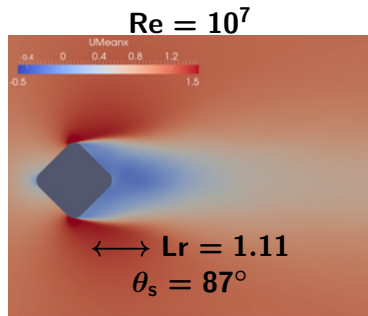
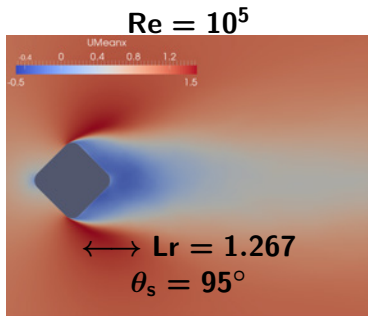
STATISTICS OF THE PRESSURE

	$\overline{C_p}$ (front)	C'_p (front)	$\overline{C_p}$ (back)	C'_p (back)
Re = 10⁵				
Expe	0.22		-1.6	
DDES	0.145 (0.23)	0.06	-1.782 (-1.7)	0.33
% diff	~-34 (+4.5)		~+11 (+6)	
Re = 10⁷				
Expe	0.17		-1.52	
DDES	0.065 (0.105)	0.07	-1.632 (-1.592)	0.3
% diff	~-61 (-38)		~ +7(4.7)	

The convergence error is estimated to be 1 – 2% for the averaged quantities and 3% for the fluctuating quantities, respectively.

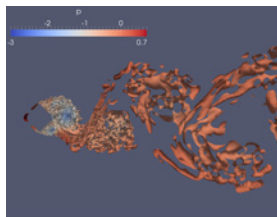
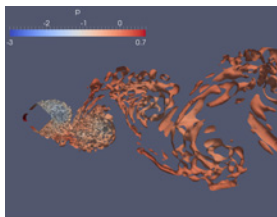
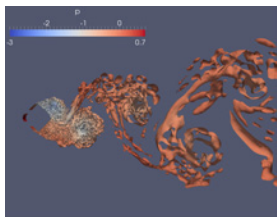
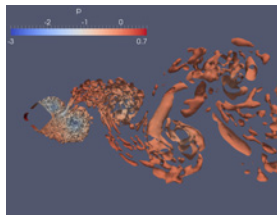
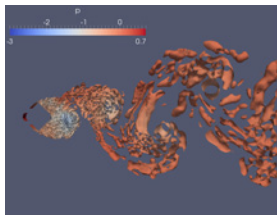
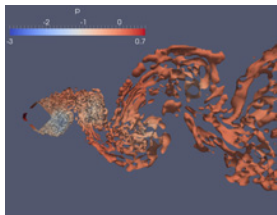
MEAN FLOW: STREAMWISE VELOCITY

- A viscosity dominated flow impinges the upstream cylinder corner
- The recirculation length slightly decreases when Re increases
- At $Re = 10^5$ and $Re = 10^7$, the flow separates slightly upstream and downstream the upper corner, respectively



INSTANTANEOUS FLOW: Q-ISOCONTOURS AT $Re = 10^7$

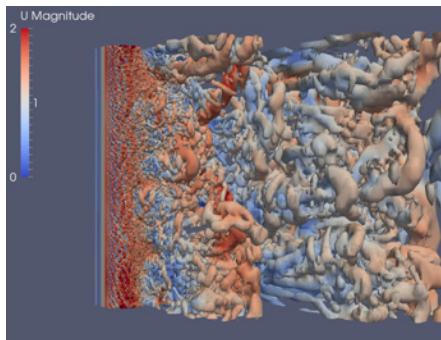
- Fine disorganized structures (KH) superimposed around the VK vortex street



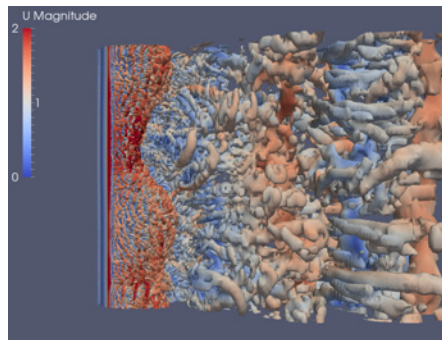
INSTANTANEOUS FLOW

- 3D flow
- well-defined hairpin vortex

$Re = 10^5$



$Re = 10^7$



Spanwise visualization of Q -isocontours

- High Reynolds flows over an inclined (45° angle of attack) square rounded shape cylinder have been modelled
- A demanding exercise for numerics: blind tests at Reynolds numbers: $Re = 10^5$ and $Re = 10^7$
- Native OpenFOAM DDES seems to provide an appropriate modelling
→ good compromise between numerical cost and accuracy, with main flow quantities in reasonable agreement with experiments
- A more detailed analysis of the flow physics is already in progress

STATISTICS OF THE PRESSURE AND RECIRCULATION LENGTH NUM/EXPE

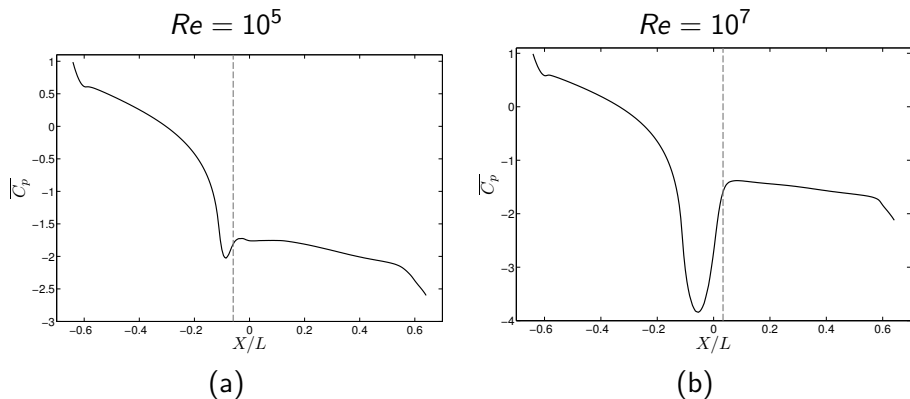
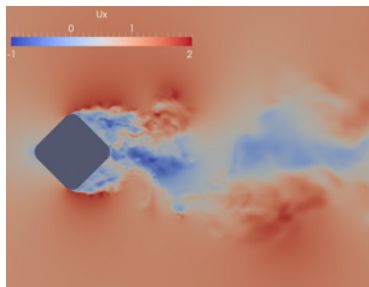


Figure : Spanwise averaged values of (a-b) the mean pressure coefficient $\overline{C_p}$. The results are shown for (left column) the case $Re = 10^5$ and (right column) the case $Re = 10^7$.

INSTANTANEOUS FLOW: STREAMWISE VELOCITY

$Re = 10^5$



$Re = 10^7$

