Non–linear Detached–Eddy Simulations on Supercomputing Facilities

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Introduction

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- Assess OpenFOAM code performance in Detached–Eddy Simulations (DES)
- Provide a contribution to the ongoing search for a better hybrid LES/RANS approach applicable to high Re flows. In particular:
  - a quadratic constitutive relation (QCR) for Reynolds Stresses introduced in [Spalart, 2000] for RANS equations is here evaluated in SA–DES environment
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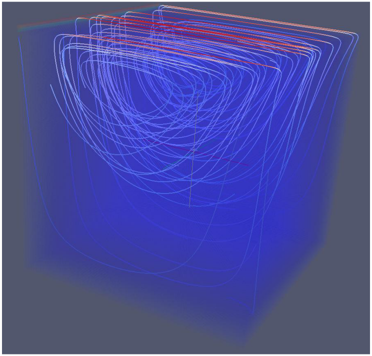
  - a standard SA–DES computation was also performed
- Perform scalability tets for OpenFOAM code on the GALILEO supercomputing facility (just installed at CINECA)

Scalabilty tests

Strong scalability tests have been conducted on GALILEO supercomputing facility @CINECA considering the following parameters:

- Total number of cells
- Linear–solvers
- Compiler/MPI implementation effect
  - GNU compilers + Open MPI (built with GNU compilers)
  - Intel®compilers + Intel®MPI library
  - Intel®compilers + Open MPI (built with Intel®compilers)
  - Intel®compilers + Open MPI (built with GNU compilers)

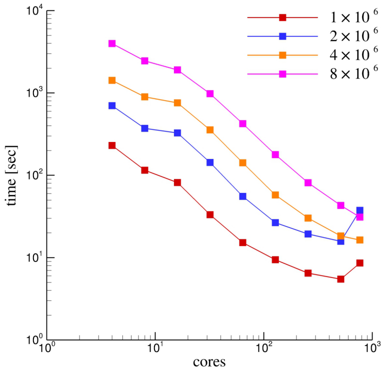
Lid–driven cavity flow



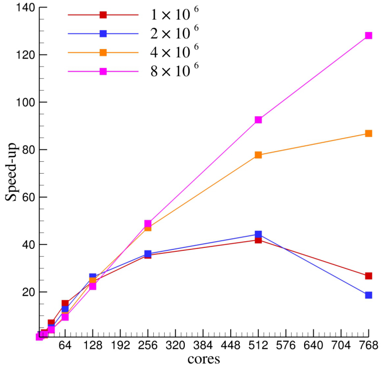
Streamlines, [Vratis Ltd, 2015]

- Cubic domain, $H = 1$, $\mathrm{Re} = 10$;
- `icoFoam` solver;
- Structured uniformly spaced grid;
- 40 time–steps without I/O as in [Culpo, 2011];
- $\Delta t = 10^{-4}$;
- Default linear–solvers:
    - PCG for p with DIC preconditioner;
    - smoothSolver for $\mathbf{u}$ (`symGaussSeidel`);
    - PISO correctors: 2;
- Default tollerances: p: 10^{-6}, $\mathbf{u}$: 10^{-5}.

Grid cells



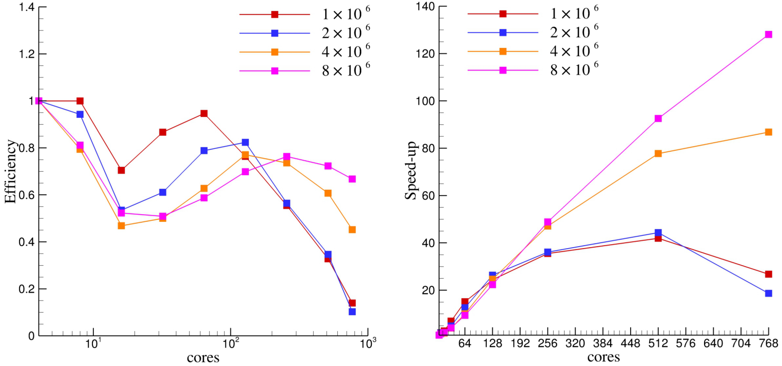
(a) CPU–time



(b) Speed-up

Figure: Effect of different total number of grid cells

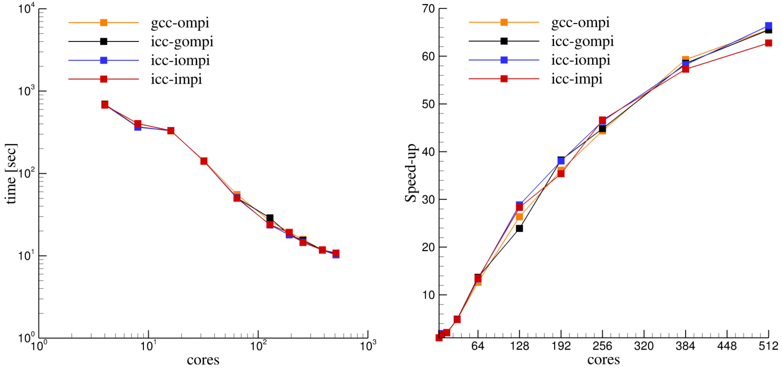
Grid cells



(a) Efficiency (b) Speed-up

Figure: Effect of different total number of grid cells

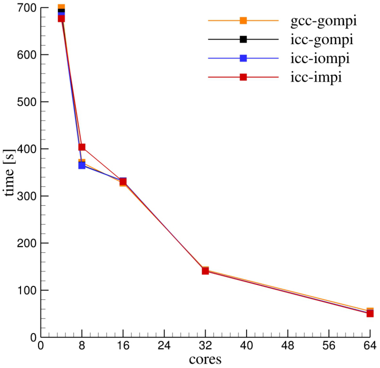
Compilers and MPI implementation



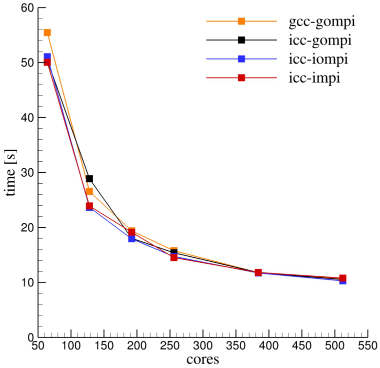
(a) CPU–time (b) Speed-up

Figure: Effect of different compilers and MPI implementations ($2 \cdot 10^6$ cells)

Compilers and MPI implementation



(a) CPU–time → 0–64 cores



(b) CPU–time → 64–512 cores

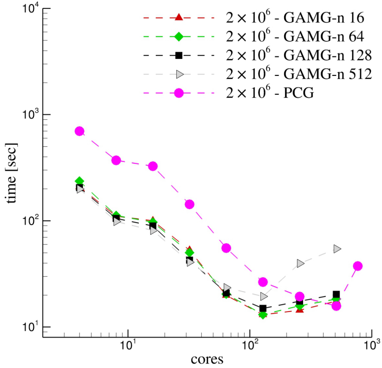
Figure: Effect of different compilers and MPI implementations ($2 \cdot 10^6$ cells)

Linear solvers

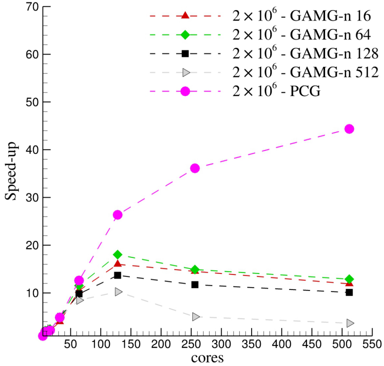
smoothSolver for **u** (`symGaussSeidel`);
PISO correctors: 2.

```
p
    {
            solver              GAMG;
            tolerance           1e-06;
            relTol              0;
            smoother            GaussSeidel;
            nPreSweeps          0;
            nPostSweeps         2;
            nFinestSweeps       2;
            cacheAgglomeration on;
            agglomerator        faceAreaPair;
            nCellsInCoarsestLevel 16-512;
            mergeLevels         1;
     }
```

Linear solvers



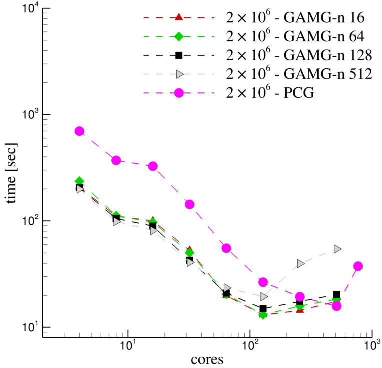
(a) CPU–time



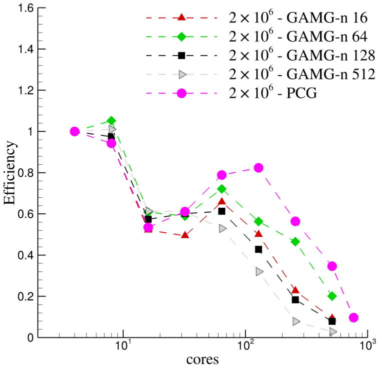
(b) Speed–up

Figure: $2 \cdot 10^6$ cells

Linear solvers



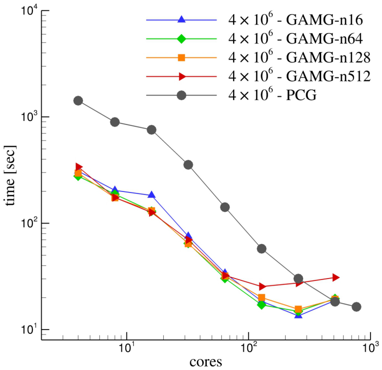
(a) CPU–time



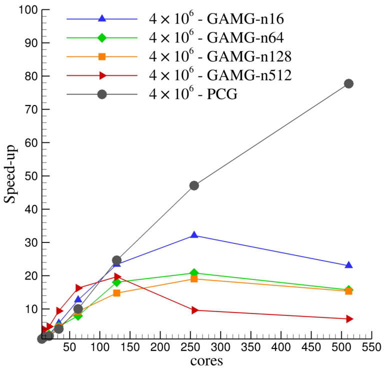
(b) Efficiency

Figure: $2 \cdot 10^6$ cells

Linear solvers



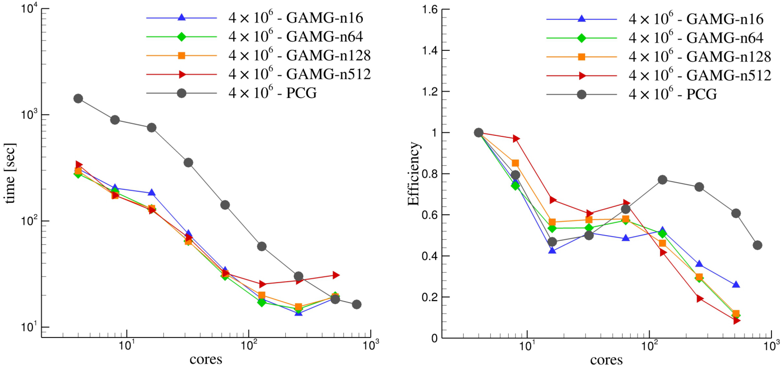
(a) CPU–time



(b) Speed–up

Figure: $4 \cdot 10^6$ cells

Linear solvers



(a) CPU–time

(b) Efficiency

Figure: $4 \cdot 10^6$ cells

DES equations

$$
\begin{aligned}
&\nabla \cdot \mathbf{u} = 0, \\
&\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = -\frac{1}{\rho} \nabla p + \nabla \cdot (2\nu \mathbf{D}) + \nabla \cdot \mathbf{B}, \\
&\frac{\partial \tilde{\nu}}{\partial t} + \nabla \cdot (\mathbf{u}\tilde{\nu}) = c_{b1} \tilde{S} \tilde{\nu} + \frac{c_{b2}}{\sigma} \nabla \tilde{\nu} \cdot \nabla \tilde{\nu} + \frac{1}{\sigma} \nabla \cdot ((\nu + \tilde{\nu}) \nabla \tilde{\nu}) - c_{w1} f_w \left(\frac{\tilde{\nu}}{\tilde{d}} \right)^2
\end{aligned}
$$

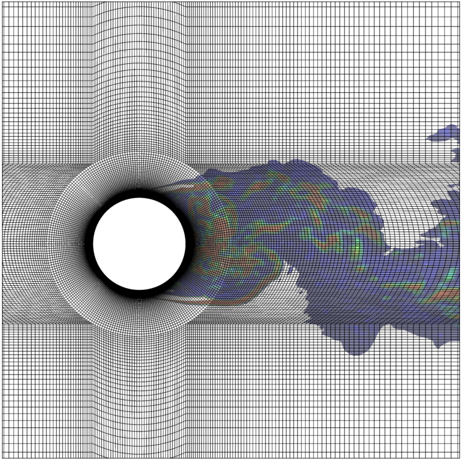
where:

$$
\begin{aligned}
&\mathbf{B} = \mathbf{R} - c_{r1} \left(\mathbf{Q} \cdot \mathbf{R} - \mathbf{R} \cdot \mathbf{Q} \right), \\
&\mathbf{R} = -\frac{2}{3} k \mathbf{I} + 2\nu_t \mathbf{D}, \quad \mathbf{Q} = 2\boldsymbol{\Omega} / \sqrt{\nabla \mathbf{u} : \nabla \mathbf{u}}, \\
&\mathbf{D} = \frac{1}{2} \left(\nabla \mathbf{u} + \nabla \mathbf{u}^T \right), \quad \boldsymbol{\Omega} = \frac{1}{2} \left(\nabla \mathbf{u} - \nabla \mathbf{u}^T \right), \quad S = \sqrt{2\boldsymbol{\Omega} : \boldsymbol{\Omega}}, \\
&\tilde{S} = S + \frac{\tilde{\nu}}{k^2 d^2} f_{v2}, \quad \nu_t = f_{v1} \tilde{\nu}, \quad \tilde{d} = \min \left(d, C_{DES} \Delta \right).
\end{aligned}
$$

DES equations

- $\mathbf{B} = \mathbf{R} - c_{r1} \left(\mathbf{Q} \cdot \mathbf{R} - \mathbf{R} \cdot \mathbf{Q} \right)$
  - it was introduced in [Spalart, 2000] for RANS equations coupled with the one–equation Spalart–Allmaras turbulence model and it allows the prediction of secondary flows
  - it is related related to the proposal of [Wilcox and Rubesin, 1980]
  - this quadratic constitutive relation is considered preliminar in the sense it uses only one of the many possibile combinations of strain rate and rotation tensor
  - $c_{r1} = 0.3$ was obtained in simple boundary layer flows requiring a fair level of anistropy $\overline{u'u'} > \overline{w'w'} > \overline{v'v'}$
  - it is turbulence model indipendent
- the closure functions and constants of the turbulence/SGS model are standard
- To assess the performance of this constitutive relation in DES envinronment the flow–field around the circular cylinder in subcritical regime ($\mathrm{Re} = 3900$) was computed

Computational Grid



- Structured non–orthogonal grid
- Rectangular domain:
  - 40 D in the wake region
  - 20 D in transverse direction
  - 0.5 D in span–wise direction
- First cell height: $2 \cdot 10^{-3} D$
- Span–wise direction: $2 \cdot 10^{-2} D$ uniform spacing
- No wall functions
- No perturbations added at the inlet
- $2.06 \cdot 10^6$ cells

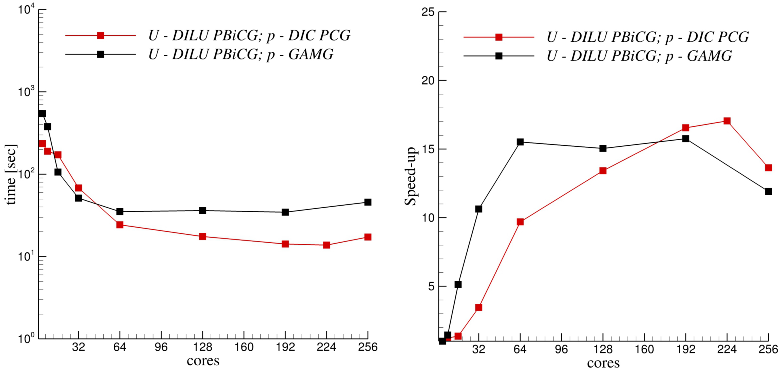
Numerics

- `pimpleFOAM` solver
- some div–terms:

```
div(phi,U)      Gauss linear;
div(phi,nuTilda) Gauss limitedLinear 0.333;
div(nonlinearStress)     Gauss linear corrected;
```

- Linear solvers:
  - Preconditioned bi-Conjugate Gradient Method with DILU for $\mathbf{u}$
  - Preconditioned bi-Conjugate Gradient Method with DILU for $\tilde{\nu}$
  - Preconditioned conjugate gradient method with DIC for p
- Tollerances: 10^{-5} for p, 10^{-12} for $\mathbf{u}$ and $\tilde{\nu}$
- second order implicit time integration ($\Delta t = 10^{-3}$)

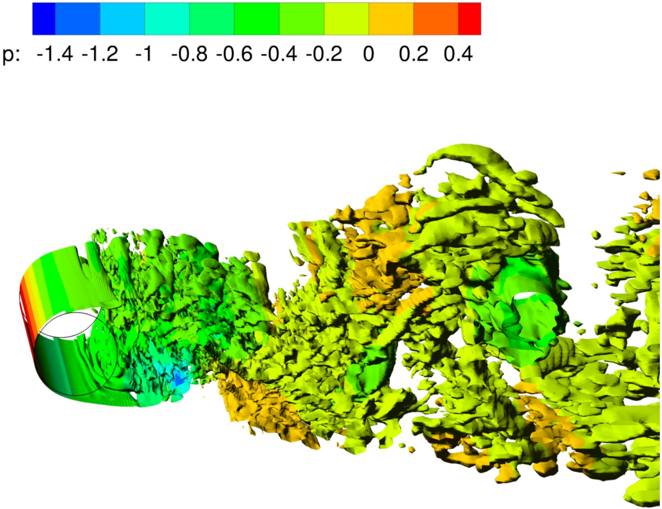
Parallel performance



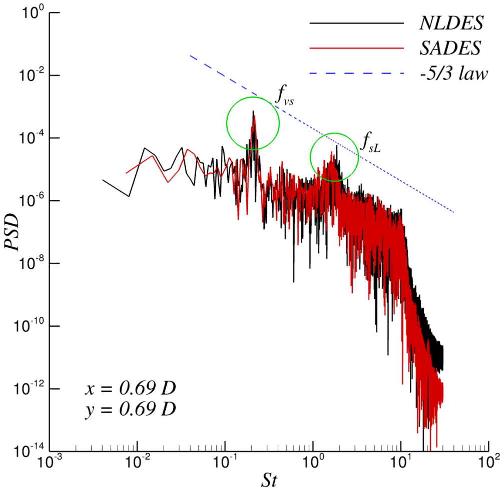
(a) CPU–time (b) Speed-up

Figure: Effect of the linear solver

Vortical structures



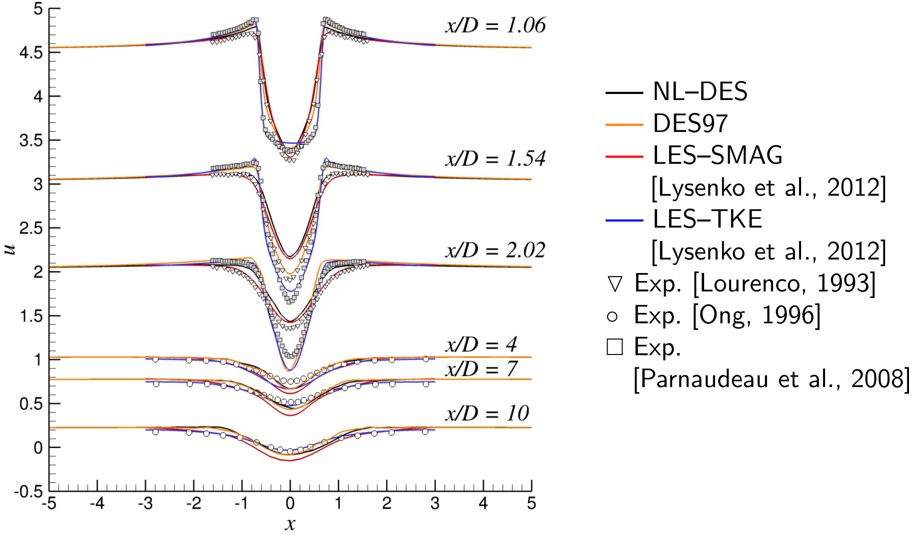
1D energy spectra



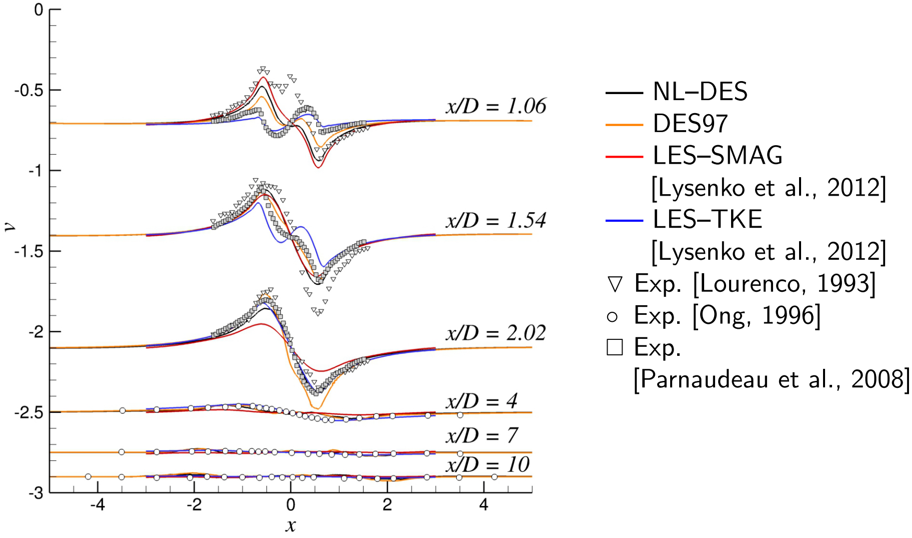
	$\mathrm{St_{vs}}$
NL–DES	$0.217 \pm 4 \cdot 10^{-3}$
SA–DES	$0.216 \pm 7 \cdot 10^{-3}$
LES–SMAG	0.19
LES–TKE	0.209
Parnaudau	0.208
Ong	0.21

	$\mathrm{St_{vs}/St_{sL}}$
NL–DES	≈ 8.7
SA–DES	≈ 7.3
LES–SMAG	≈ 8
LES–TKE	≈ 7
Dong (DNS)	7.83

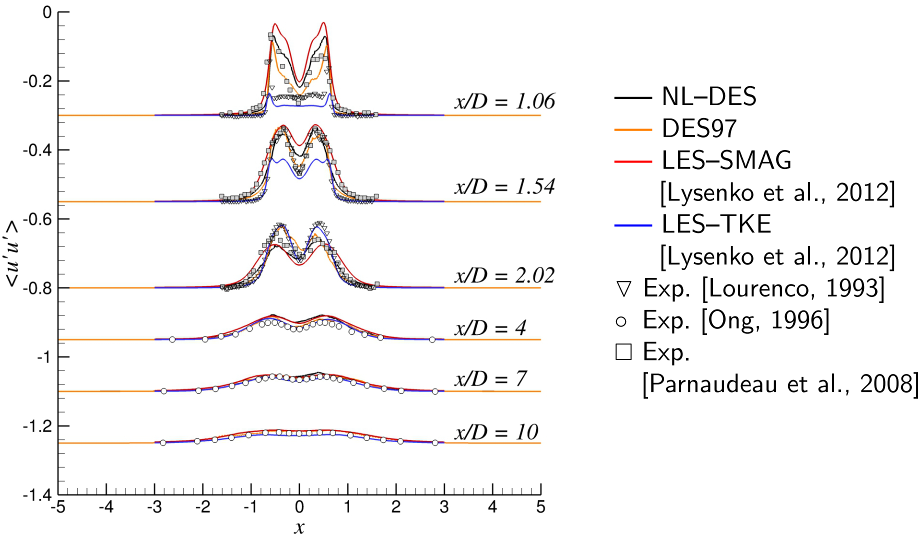
Mean–velocity profiles



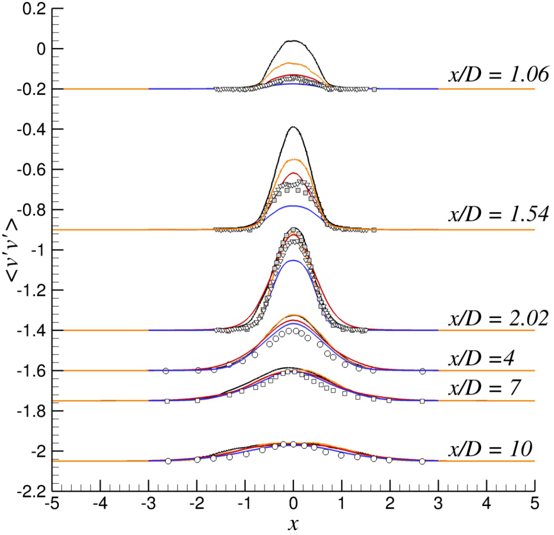
Mean–velocity profiles



$\overline{\mathbf{u'u'}}$ profiles



$\overline{v'v'}$ profiles



— NL–DES
— DES97
— LES–SMAG [Lysenko et al., 2012]
— LES–TKE [Lysenko et al., 2012]
▽ Exp. [Lourenco, 1993]
○ Exp. [Ong, 1996]
□ Exp. [Parnaudeau et al., 2008]

Aerodynamic forces

	$C_{l,rms}$	$C_{d,rms}$	$\langle C_l \rangle$	$\langle C_d \rangle$
NL–DES	0.3988	1.1374	0.0052	1.1374
SA–DES	0.2872	1.0657	0.0091	1.0602
LES–SMAG [Lysenko et al., 2012]	0.444	1.19	0.44	1.18
LES–TKE [Lysenko et al., 2012]	0.089	0.97050	0.09	0.97
[Ouvrard et al., 2010] LES	0.092	–	–	0.99
[Meyer et al., 2010] LES	–	–	–	1.05
[Kravchenko and Moin, 2000] LES	–	–	–	1.04
[Mittal and Moin, 1997] LES	–	–	–	1.00
[Franke and Frank, 2002] LES	–	–	–	0.99
[Alkishriwi et al., 2006] LES	–	–	–	1.05
[Mani et al., 2009] LES	–	–	–	0.99
[Wornom et al., 2011] LES	0.11	–	–	0.99
[Lourenco, 1993] PIV	–	–	–	0.99
[Norberg, 1994] HWA	–	–	–	0.98

Conclusions

- OpenFOAM scalability have been tested on GALILEO with good results.
- NL–DES (using a simple quadratic constitutive relation) and SA-DES97 have been compared in this work. NL–DES seems to be promising (our results are not still full converged).
- Further topics must be addressed:
  - span–wise resolution
  - others constitutive relations
  - DDES/IDDES

Acknowlegments

- We acknowledge Dr Ivan Spisso and CINECA for the invitation to this workshop and for the activation of a trial project on GALILEO for its testing.
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