IMPROVED LES OF TURBULENT CHANNEL FLOW BY USING OPENFOAM WITH THE EXPLICIT ALGEBRAIC SGS MODEL

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Abstract

Wall-resolved large-eddy simulation (LES) of turbulent channel flow is carried out using OpenFOAM with the Explicit Algebraic sub-grid scale model (EAM) by Marstorp *et al.* *(J. Fluid Mech., 2009)* and the Dynamic Smagorinsky model (DSM). Particular efforts have been made on an accurate and low-diffusive implementation in the framework of a general purpose 2nd order finite volume CFD solver.

The use of EAM improves the prediction and relaxes the resolution requirements for LES of moderately high Reynolds numbers in comparison with DSM. Results and conclusions are qualitatively consistent with previous results obtained by the use of a higher-order spectral solver.

1 Introduction

Wall-resolved LES of wall-bounded flows at high Reynolds numbers are proven to be very demanding in terms of the computational requirements [10]. In order to obtain an accurate prediction of such flows while optimizing the use of computational resources available, there are two possible approaches. A first possibility consists of techniques like hybrid RANS/LES and detached-eddy simulation (DES) or other wall-modelling approaches. However, these methods might be dependent on subtle modelling and meshing details resulting in occasional mismatch between the mean velocity profile in the different zones within the boundary layer([11], [4]).

The alternative proposed here, although more restricted in terms of the Reynolds number, is to perform wall-resolved LES adopting a more advanced sub-grid scale (SGS) modelling, through the use of the Explicit Algebraic SGS model (EAM).

2 Mathematical formulation

The EAM is non-linear and derived from the modelled transport equations of SGS stress anisotropy. The expression for the modelled stress tensor reads:

$$\tau_{ij} = \frac{2}{3}\delta_{ij}K_{SGS} + \underbrace{\beta_1 K_{SGS}\widetilde{S}^*_{ij}}_{eddy-viscosity} + \underbrace{\beta_4 K_{SGS}(\widetilde{S}^*_{ik}\widetilde{\Omega}^*_{kj} - \widetilde{\Omega}^*_{ik}\widetilde{S}^*_{kj})}_{\substack{anisotropy\ of \\ SGS\ stresses}}\,. \tag{1}$$

where τ_{ij} is the SGS stress tensor, and $\widetilde{S}^*_{ij}$ and $\widetilde{\Omega}^*_{ij}$ are the resolved strain and rotations rate tensors, respectively, normalized by the SGS time scale τ^*. K_{SGS} is the SGS kinetic energy, modelled as

$$K_{SGS} = c\widetilde{\Delta}^2|\widetilde{S}_{ij}|^2, \tag{2}$$

$\widetilde{\Delta}$ is the filter scale, and model coefficient c is dynamically computed using a test filter and the Germano identity. β_1 and β_4 are model coefficients and depend on $\widetilde{S}_{ij}$ and $\widetilde{\Omega}_{ij}$. The second term on the right-hand-side of (1) is an eddy-viscosity term while the third non-linear term aims to improve the modelling of τ_{ij} in regions of strong anisotropy. Previous studies have proven that EAM significantly improves LES of rotating and non-rotating wall-bounded turbulent flows ([5], [8], [9]). A recent study by [6], where a pseudo-spectral code is employed, has shown that LES with EAM is more accurate especially at coarse resolutions, than the eddy viscosity SGS models like the dynamic Smagorinsky model (DSM). Large differences in the prediction of the Reynolds stress tensor components and the mean velocity profiles are noticeable for a range of friction Reynolds number starting from $Re_\tau \approx 550$ up to $Re_\tau \approx 5200$. The friction Reynolds number is based on the friction velocity and the channel half-width and the streamwise grid spacing is $\Delta x^+ \approx [157, 270]$, while the spanwise one is $\Delta z^+ \approx [63, 108]$ in the LES. The better performance of the EAM can be attributed to the third term on the right-hand-side of (1), which gives a significant contribution near the wall.

3 Results

The present study aims to answer the following question: could EAM reproduce similar performances in a general purpose CFD code where the order of accuracy is substantially lower? For this purpose, the EAM has been implemented in OpenFOAM, and LES of incompressible turbulent channel flow has been performed using the DSM, the EAM and no SGS model (NM), at the friction Reynolds numbers of 395, 550 and $Re_\tau = 950$. Note that the implementation of the DSM, consistent with the formulation in [2], is also part of the study. All the simulations have a constant mass flux constraint, such that the bulk Reynolds number is the same as the DNS of [7] and [3], and the resolution used is $(\Delta x^+, \Delta z^+) \approx (41, 27)$.

For the $Re_\tau = 395$ case a parameter study has been carried out, in order to find the optimal numerical setup, used for all the LESs. By varying β_p as the parameter that controls the influence of the Rhie and Chow (R&C) interpolation in the solver, the consequent numerical dissipation is manipulated. This approach is similar to the method adopted in Code_Saturne [1], where the Arakawa coefficient is used. Note that the authors assume that this approach most likely cannot be applied in more complex (*e.g.* industrial) configurations without side-effects.

The analysis of the skin friction has been considered as a first step of the study. In figure 1 the friction coefficient ratio between LES and DNS has been considered as a function of the case number, which increases with the resolution (*e.g.* case 0 and case 3 have a resolution of $(\Delta x^+, \Delta z^+) \approx (165, 108)$ and $(\Delta x^+, \Delta z^+) \approx (41, 27)$, respectively). A substantial difference in the prediction of the friction coefficient is noticeable when the R&C interpolation is suppressed. At the finest resolution, the use of the standard OpenFOAM solver (with $\beta_p = 1.0$, values denoted with the cross in figure 1) introduces an additional numerical dissipation which strongly contributes to the underestimation of the skin friction, independently of the choice of the SGS model. R&C interpolation switched off, the friction coefficient ratio follows a monotonic increasing trend with increasing resolution, consistent with what has been found in [6]. The computation of the skin friction by LES with the EAM shows to be more accurate than LES with DSM and with no SGS model, for all the resolutions considered. With the finest resolution, the predicted friction coefficient by LES with EAM has even come close to the DNS value.

A similar behaviour has been experienced for the $Re_\tau = 950$ case.

Figure 2 a) shows the mean velocity profile as a function of the wall-normal direction in wall units, with different values of β_p. $\beta_p = 0.01$ leads to a quasi-negligible R&C effect, while it becomes maximal when $\beta_p = 1.0$, which is the default scheme in OpenFOAM. The mean velocity profile, like the components of the Reynolds stress tensor (not shown here), is strongly affected by the R&C interpolation, and the difference is remarkable from the end of the

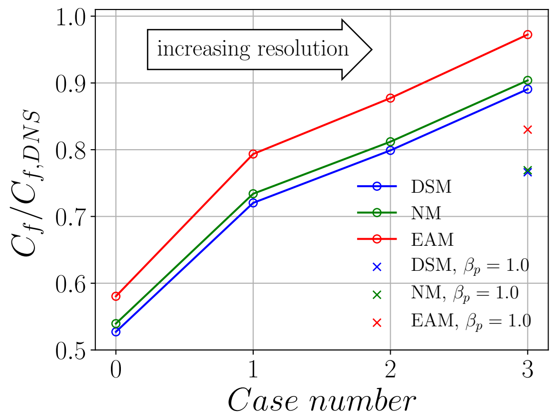

Figure 1: Friction coefficient ratio between LES and DNS, $Re_\tau \approx 550$.

viscous wall region up to the whole outer layer. Thus, the R&C interpolation introduces a non-negligible numerical dissipation that has been reduced by setting the value of $\beta_p = 0.01$ for the following simulations, while retaining numerical stability. Figure 2 b) shows the mean velocity profile for $Re_\tau \approx 550$. Here we can see how crucial is the choice of an anisotropy-resolving model like the EAM for the correct estimation of the skin friction and the mean streamwise velocity. LES with EAM is able to reproduce a correct mean velocity profile for the whole channel domain. On the other hand, LES with DSM and NM underpredict the skin friction resulting in an overpredicted $< U >^+$ compared with the DNS results from $y^+ \approx 10$ up to the centre of the channel.

In order to understand in a clearer way the effect of the R&C interpolation at the smallest scales, we have generated visualizations of the instantaneous streamwise velocity fluctuations along the horizontal plane, at a wall-normal distance of $y^+ \approx 10$, for $Re_\tau \approx 550$. The LES performed with the R&C interpolation and the DSM (figure 3 a)) exhibits an overestimation of the amplitude of the structures close to the wall, which also present a longer streamwise extension. In contrast, LES with DSM with $\beta_p = 0.01$ (figure 3) captures a larger amount of small turbulent structures, which are better predicted by using the EAM and $\beta_p = 0.01$ (figure 3).

Differences between LES with DSM and LES with EAM becomes larger when the pseudo-spectral code is employed, while LES with EAM have a comparable behaviour to the one with OpenFOAM.

Other simulations, performed at $Re_\tau = 950$ and using the same resolution in inner units, confirms the behaviour of the EAM, and results will be included in the presentation.

4 Conclusions

LES of turbulent channel flow using OpenFOAM

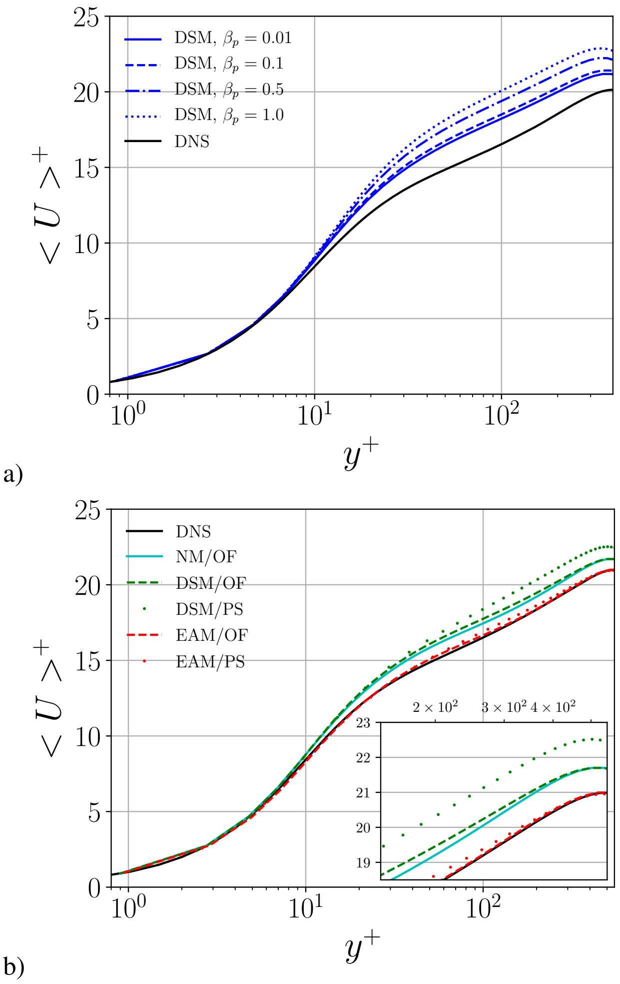

Figure 2: (a) Mean streamwise velocity at $Re_\tau \approx 395$ in wall units, as a function of the inner units-scaled wall-normal direction, for different β_p coefficients. (b) Mean streamwise velocity at $Re_\tau \approx 550$ in wall units, as a function of the inner units-scaled wall-normal direction. Solid lines refer to the LES by using OpenFOAM (OF), while dashed to the LES using the pseudo-spectral code (PS), with a resolution of $(\Delta x^+, \Delta z^+) \approx (144, 58)$, from [6].

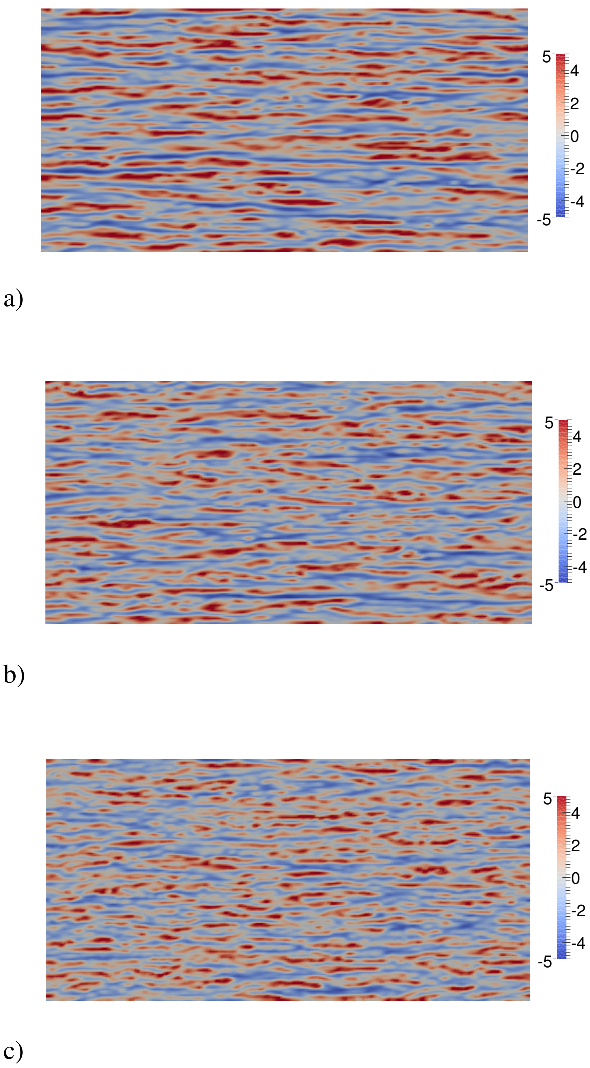

Figure 3: Horizontal snapshots of the streamwise velocity fluctuations, normalized with the friction velocity u_τ, at $y^+ \approx 10$, for $Re_\tau \approx 550$, of a) LES with DSM and $\beta_p = 1.0$, b) LES with DSM and $\beta_p = 0.01$, c) LES with EAM and $\beta_p = 0.01$.

with the modified numerics and the EAM are in reasonably good agreement with DNS results, while the other LESs fail. Therefore, the use of EAM with the modified numerics is a promising setup in order to achieve higher accuracy with a reasonable computational cost in wall-resolved LES of wall-bounded flows at moderately high Reynolds numbers with OpenFOAM.

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