LARGE-EDDY SIMULATION OF TURBULENT CHANNEL FLOW USING THE EXPLICIT ALGEBRAIC SUBGRID-SCALE MODEL

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Abstract Large-eddy simulation (LES) of turbulent channel flow are performed with a new subgrid-scale (SGS) stress model. The simulations show that with this model we can well predict turbulent wall flows at coarse resolutions and moderately high Reynolds numbers. The commonly used dynamic Smagorinsky model fails at coarser resolutions.

The goal of our study is to examine if LES can accurately predict wall-bounded turbulent flows at moderately high Reynolds numbers at acceptable computational costs requiring relatively coarse resolutions. In particular, we are interested in the performance of our recently developed explicit algebraic subgrid-scale (SGS) stress model (EASSM) for LES [1]. The EASSM is non-linear and is derived from the modelled transport equations of the SGS stress anisotropy following the approach that led to the explicit algebraic Reynolds stress model in [2] and reads

$$\tau_{ij} = \frac{2}{3}\delta_{ij}K^{SGS} + \beta_1 K^{SGS}\tilde{S}^*_{ij} + \beta_4 K^{SGS}(\tilde{S}^*_{ik}\tilde{\Omega}^*_{kj} - \tilde{\Omega}^*_{ik}\tilde{S}^*_{kj}). \tag{1}$$

Here τ_{ij} is the SGS stress tensor, and $\tilde{S}^*_{ij}$ and $\tilde{\Omega}^*_{ij}$ are the resolved strain and rotation rate tensors, respectively, normalised by the SGS time scale τ^*. K^{SGS} is the SGS kinetic energy modelled as

$$K^{SGS} = c\tilde{\Delta}^2|\tilde{S}_{ij}|^2. \tag{2}$$

$\tilde{\Delta}$ is the filter scale, and model coefficient c is dynamically determined using the Germano identity. β_1 and β_4 are model coefficients and depend on S_{ij} and Ω_{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 case of strong anisotropy.

Tests have shown that the EASSM significantly can improve LES of rotating and non-rotating wall-bounded turbulent flows [1, 3, 4]. Especially at coarse resolutions LES with the EASSM are more accurate than with eddy viscosity SGS models like the often used dynamic Smagorinsky model. The better performance of the EASSM can be attributed to the third term on the right-hand-side of (1) which gives a significant, important contribution near the wall.

A large number of other SGS models have been developed in the recent decades but many of them have been validated in LES of turbulent channel flow at low Reynolds numbers and relatively fine spatial resolutions. LES of turbulent wall flows at even moderately high Reynolds numbers would be computationally prohibitively expensive using these fine resolutions. Our aim is to investigate if LES is able to correctly predict e.g. the skin friction and mean velocity profile with the emerging log-layer in turbulent channel flow at moderately high Reynolds numbers at reasonable computational costs requiring coarser spatial resolutions. We are especially interested in the performance of our EASSM since our previous work has indicated that the improved modelling of the SGS anisotropy is particularly important at coarser resolutions.

To this end, we have carried out LESs of turbulent plane channel flow at two bulk Reynolds numbers corresponding to the DNSs of [7] with $Re_\tau = 2003$, based on friction velocity and channel half-width, and [6] with $Re_\tau = 934$ [3, 5]. The LESs are performed with a pseudo-spectral code at four different resolutions using the EASSM and the dynamic Smagorinsky model (DSM) with a constant mass flux constraint. The streamwise grid spacing is about 75 up to 180 and the spanwise grid spacing is about 30 up to 90 in wall units. These resolutions are coarse compared to the DNS resolutions, which are 12 and 6 in the streamwise and spanwise direction respectively in wall units, as well as many other LES of turbulent wall flows.

Figure 1.*a* shows the mean velocity profiles in wall units at the two Reynolds numbers and four different resolutions. At both Reynolds numbers the LESs with the DSM deviate significantly from the DNS and only comes closer to the DNS when the resolution is increased. By contrast, the LESs with the EASSM show much less variation with resolution and are close to the DNS at both Reynolds numbers. Profiles of the streamwise, wall-normal and spanwise Reynolds stresses in wall units are shown in figure 1.*b*, *c* and *d* respectively. Here again the LESs with the DSM show a considerable variation with resolution while the LESs with the EASSM are much more resolution independent and closer to the DNS at both Reynolds numbers. The LESs with the DSM show the typical over-prediction of the streamwise and under-prediction of the wall-normal Reynolds stresses.

Since the bulk Reynolds number is the same in the LESs and DNS the friction Reynolds number Re_τ and thus the mean wall shear stress and imposed mean pressure gradient are not necessarily the same in the LESs and DNS. The mean wall shear stress or imposed pressure gradient is in fact a key quantity but is severely under-predicted, about 20% by LES with the DSM at the coarsest resolution. Only at higher resolution the LES prediction comes close to the DNS result while again the LES with the EASSM is reasonably close to the DNS at all four resolutions. Further spectral analysis shows that, although the near wall structures are not very well captured at these coarse resolutions, the typical very large-scale

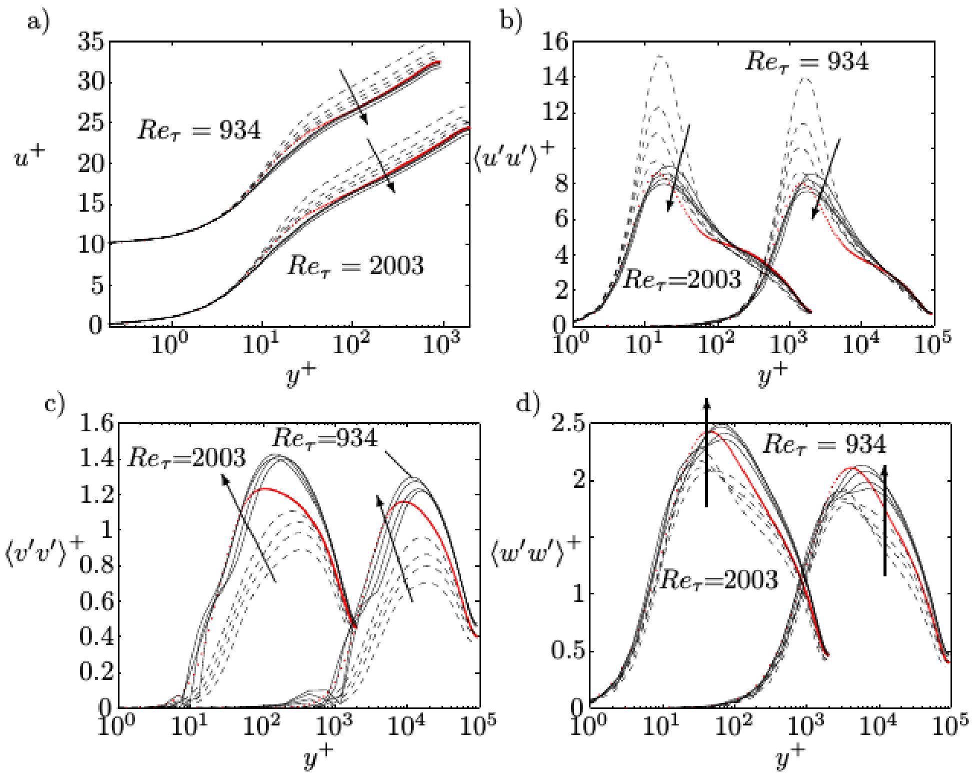

Figure 1. a) Mean velocity profiles in wall units. Profiles are shifted in the ordinate direction to separate the two Reynolds numbers. b-d) Mean streamwise $\langle u'u' \rangle^+$, wall-normal $\langle v'v' \rangle^+$ and spanwise $\langle w'w' \rangle^+$ Reynolds stresses in wall units. Predictions of the two Reynolds numbers are separated by a shift in the abscissa direction. Arrows point in the direction of increasing resolution. — : EASSM, - - : DSM and · · ·: DNS from [6, 7].

structures at these high Reynolds numbers are reasonably well captured by the LESs [3]. The better results of the LESs with EASSM can be attributed to a better prediction of the SGS dissipation and anisotropy near the wall [3].

To summarise, LESs with the EASSM are in reasonable to good agreement with DNS of turbulent channel flow up to $Re_\tau = 2003$ even at coarse resolutions while LESs with the DSM significantly deviate from DNS at coarser resolutions. In order to obtain comparable good results for the mean wall shear stress and velocity profiles the LESs with the DSM need $O(10)$ more grid points than the LESs with the EASSM. Consequently, eddy viscosity SGS stress models like the DSM do not seem to be very suitable for LES of higher Reynolds wall-bounded turbulent flows and more advanced models like the EASSM with a better description of the near wall anisotropy appear to be necessary to keep the computational costs acceptable for LES of such flows.

The aim is to further analyse the LES results and to carry out LESs of turbulent channel flow at $Re_\tau = 5200$ using the EASSM and compare with the recent DNS of [8]. In the DNS an unequivocal log-layer starts to emerge at this Reynolds number. An important question is if LES is able to reproduce this log-layer with the correct slope and other characteristics of channel flow that appear at this Reynolds number at reasonable computational costs and thus quite coarse resolutions.

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