EVALUATION OF DELAYED DETACHED-EDDY SIMULATION FOR CHANNEL FLOW AT REYNOLDS NUMBER 2800

Zhigang WEI¹ and Yaojun GE²
¹PhD Student, Department of Bridge Engineering, Tongji University
Shanghai 200092, P.R. China, 99dlw@tongji.edu.cn
²Professor, Department of Bridge Engineering, Tongji University
Shanghai 200092, P.R. China, yaojunge@tongji.edu.cn

ABSTRACT

Delayed detached-eddy simulation (DDES) is assessed in a turbulent channel flow simulation at \(Re=2800\). DDES is applied as a wall-modeling of large-eddy simulation (LES). The Navier–Stokes equations are solved with three different grid resolutions by using a co-located finite-volume method. The results are compared with direct numerical simulation (DNS), full large-eddy simulation (full-LES) and detached-eddy simulation (DES). Dynamic model is used in LES, which assumes a similarity of the subgrid and the subtest Reynolds stresses and an explicit filtering operation is required. Traditional Spalart-Allmaras model is implemented in DES. The dimensionless distance of the first grid point away from the solid wall is 0.7 approximately, and the grid spacings parallel to the wall in three meshes vary from 18 to 71 in dimensionless unit. It is observed DDES does not improve the results comparing with origin DES. Both DES and DDES in their own gridding policy has shown some strange behaviour, like unstable results. And grid design at low Reynolds numbers for DDES is also difficult to meet the need. It is then concluded that DDES and DES are not very suitable for wall-modeling of LES at low Reynolds numbers.

KEYWORDS: DELAYED DETACHED-EDDY SIMULATION, DETACHED-EDDY SIMULATION, LARGE-EDDY SIMULATION, CHANNEL FLOW, TURBULENCE, NEAR-WALL MODELING

Introduction

Channel flow is well understood by both Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES), it serves as a basic test for these two techniques. It also provides us a platform to study wall-bounded turbulence, especially in attached flows research. Channel flow at many Reynolds numbers were simulated during last two decades, among which \(Re=180, 395, 590, 2320\), are the most famous in DNS.

On the other hand, Detached-Eddy Simulation (DES) and its revision Delayed Detached-Eddy Simulation (DDES) is designed for massively separated flow by Spalart, and convincingly more capable presently than either Unsteady Reynolds-averaged Navier-Stokes (URANS) or LES. This has also been well accepted in the CFD community. As LES is increasingly convinced to be unaffordable for many industrial flows in the near future, more and more researching efforts are being devoted to hybrid RANS-LES method. This is also the case of attached flows. However, because attached flows like channel flow, their turbulence state is mostly dominated by the near-wall "streak cycle", hybrid RANS-LES methods like DES and DDES which treat near-wall region in a RANS way, will inevitably have a difficult time. In 2000, Nikitin etc., gave the first try to use DES spirit as a wall modeling of LES, and from that time on, DDES, Improved DDES (IDDES) are all published with a section to treat channel flow cases. Yet it has to be noted, till to now some unsatisfactory behaviour of DES and DDES's in channel flow simulation still remain, such as log-layer mismatch, etc.

The current research is aimed to be a stretch of Nikitin's study, we pay special attention here to low Reynolds numbers, the classic channel flow case at \(Re=180\) (Reynolds number
$Re_b=2800$ based on the bulk velocity) is selected in our study, DDES as well as DES being used as wall-modeling of LES is evaluated at this low Reynolds number.

Many of the DNS and LES simulation of channel flow over the past years are based on spectral methods, where the idea of filtering is realized ideally. In this study, finite-volume method is used. In the next section, the numerical methods and the configurations of channel flow simulation are described, with some discussion of grid design. In Sections 3, the results are discussed. The conclusions are drawn in Section 4.

Configuration and Numerical methods

The channel flow case is a fully developed turbulent flow in a channel with a bulk Reynolds number of 2800 defined as $Re_b=U_b\delta/\nu=2800$, where $U_b$ is the bulk velocity and $\delta$ is half of the channel height $H$ (see Figure 1). This approximately equals a wall shear velocity based Reynolds number: $Re_s=U_s\delta/\nu=180$, where $U_s=(\tau_w/\rho)^{1/2}$ is the wall shear velocity and $\tau_w$ is the wall shear stress. The parameters have the following values: $H=1m$, $U_b=1$m/s and $\nu=1.786\times10^4$m$^2$/s. Figure 1 shows a schematic picture of the channel. Periodic boundary conditions are applied in the streamwise and in the spanwise directions, where the lengths of the domain are $3.2H$ and $1.6H$, respectively. These distances are actually half of those used by Kim et al., in their direct numerical simulation, which is $4\pi\delta\times2\delta\times2\pi\delta$. They utilized a spectral method and $192\times129\times160$ grid points in the $x$-, $y$- and $z$-directions, respectively. In the wall normal direction, 64 cells are used and the height of the two closest cells next to the walls is $y^+=1$ in dimensionless units.

The stretching ratio of the cells is 1.10 in the wall direction. The cell height next to the centre line is 16.8 in wall unit. Calculations are carried out with three different grids, whose streamwise and spanwise cell densities vary. The parameters are given in Table 1. The streamwise length of the box in dimensionless units is approximately $1140\Delta x^+$. The periodic boundary conditions are set for all the variables.

Figure 1. The computational domain in the channel flow. Periodic boundary conditions are applied in the streamwise ($x$) and the spanwise directions ($z$). Solid walls restrict the inhomogeneous direction ($y$).

<table>
<thead>
<tr>
<th>Case</th>
<th>Grid</th>
<th>$N_x$</th>
<th>$N_y$</th>
<th>$N_z$</th>
<th>$\Delta x^+$</th>
<th>$\Delta y_{min}$</th>
<th>$\Delta y_{max}$</th>
<th>$\Delta z^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LES-C</td>
<td>Coarse</td>
<td>16</td>
<td>64</td>
<td>16</td>
<td>71</td>
<td>1.0</td>
<td>16.8</td>
<td>36</td>
</tr>
<tr>
<td>LES-M</td>
<td>Medium</td>
<td>32</td>
<td>64</td>
<td>32</td>
<td>36</td>
<td>1.0</td>
<td>16.8</td>
<td>18</td>
</tr>
<tr>
<td>LES-F</td>
<td>Fine</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>18</td>
<td>1.0</td>
<td>16.8</td>
<td>9</td>
</tr>
<tr>
<td>DES-C</td>
<td>Coarse</td>
<td>16</td>
<td>64</td>
<td>16</td>
<td>71</td>
<td>1.0</td>
<td>16.8</td>
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<td>DES-M</td>
<td>Medium</td>
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<td>16.8</td>
<td>18</td>
</tr>
<tr>
<td>DDES-C</td>
<td>Coarse</td>
<td>16</td>
<td>64</td>
<td>16</td>
<td>71</td>
<td>1.0</td>
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</tbody>
</table>

DES was first proposed by Spalart in 1997, which can also be denoted as DES97, the standard formula of DES which can be dated back to 1992, Spalart-Allmaras one-equation
model (S-A model), was presented in 2000 by Nikitin. The length scale $d$ in S-A model is now replaced with $\tilde{d}$. The $C_{DES}$ number is calibrated as 0.65 in 1999.

Delayed detached-eddy simulation was published as a revision of DES by Spalart in 2006, it is expected to have more flexibility in ambiguous grids. It was observed that DES has some drawbacks. It exhibits an incorrect behavior in thick boundary layers and shallow separation regions. This behavior begins when the grid spacing parallel to the wall becomes less than the boundary layer thickness $\delta$, either through grid refinement or boundary layer thickening. Meanwhile, a strongly increased value of the eddy viscosity in free shear layer is observed by M. Breuer.

Different from DES, in DDES, the length scale $\tilde{d}$ is replaced by

$\tilde{d} \equiv d - f_\gamma \max(0, d - C_{DES}\Delta)$ \hspace{1cm} (2)

as can be referred to its publication. Where $d$ is the distance to the nearest wall and expresses the (inviscid) confinement of the eddies by that wall. Note $\Delta$ is the cube root of the cell volume, the original DES97 defines $\Delta \equiv \max(\Delta x, \Delta y, \Delta z)$.

After the publication of DDES, it is reported the log-layer mismatch is not resolved by DDES. It is true that regarding the fidelity of the fields, any type of wall modeling will produce unrealistic coherent structures in a kind of “super-buffer layer” at the bottom of the LES region. But our motivation is to see the ability of DES and DDES as a wall-modeling "at low Reynolds numbers" just as what Nikitin did, and to compare the results with DNS and full-LES.

Concerning the grid design, it is already not easy for LES or RANS, but DES compounds the difficulties. Gridding in channel flow is not so hard as in industrial flows, but there are still some issues that have to be addressed. DES's derivative use as wall modeling of LES initialized by Nikitin in 2000 has shown its capability in a "DES grid". The term "DES grid" is used against "LES grid" that has to be carefully designed for DES97. "DES grid" refers to creating a "RANS grid" with a large spacing $\Delta||$ parallel to the wall, compared with a boundary-layer thickness: $\Delta|| \gg \delta$. In the separated regions, good accuracy is expected once the grid spacing in all directions is far smaller than the size of the region: $\Delta \ll \delta$. But when DES97 is applied to a "LES grid" with $\Delta|| \ll \delta$, it behaves as a subgrid-scale (SGS) model with built-in wall modeling. In the core region of the channel we have $\Delta|| \approx \Delta$. And this gridding strategy is not changed in DDES and IDDES.

We believe $N_y=32$ is too coarse to sustain any turbulence, actually all the cases in Nikitin's paper used $N_y\geq64$, from Re=180 to Re=80000. Simulation has shown 64 grid number in y direction is fine enough to capture the precise velocity profile. In the next section, we will see the results has shown the first grid is indeed placed below $y^+=1$, nearly 0.7. The stretching ratio in y direction is less than 1.1. Near the center of the channel, i.e. the core region, it is commonly preferred $\Delta|| \approx \Delta$. But this is hardly possible for low Reynolds numbers. As far as $\Delta||$, many circles among DES community aim to get an unlimited spacing parallel to the wall, of course, it could not be completely unlimited. So the question is, "what is this limit?"

Wall resolved LES is also called QDNS, most LES practitioners would adopt a ratio around $\Delta x^+ / \Delta z^+ = 3$, the idea is based on the knowledge of streak shapes and their spacing reported in these two decades. Though in many industrial flows, the wall shear direction is not known as a "a priori", but in channel flow case we are more confident about the main flow direction, and we keep all our cases shown in Table 1 with $\Delta x^+ / \Delta z^+ = 2$, so we are able to use $\Delta||$ to refer to both $\Delta x^+$ and $\Delta z^+$ in a quite consistent way. In Nikitin's argument, "A first estimate is that $\Delta||$ should be at least several hundred, since a typical streak spacing is 100." But this is almost unprocurable for low Reynolds numbers. As shown in Table 1, our best try is to set $\Delta x^+$ no larger than 71, simulations with $\Delta x^+$ larger than 71 will eventually cause turbulence "dies". And on the other hand, simulation with $\Delta x^+$ less than 18, has already lost it's meaning as wall
function of LES. In a word, from the gridding point, it becomes very clear that DES spirit is more suitable for high Reynolds numbers.

Results and discussion

The initial velocity profile for the simulation is

$$U_{int} = U_b \left(1 - \cos \left(4\pi \frac{y}{H}\right) \right)$$ (1)

The flow seems to find a false steady solution, unless it is provoked with an initial condition that produces a lot of vorticity. This causes an earlier transition to turbulence and reduces the simulation time. LES with the coarse, medium and fine grids are called LES-C, LES-M and LES-F, and so are DES-C, DES-M, DDES-C, DDES-M. We do not use DES-F and DDES-F as explained in the preceding section. The CFL numbers are controlled to below 0.1, 0.1 and 0.2 in the coarse, medium and fine grids, respectively. The corresponding time-step sizes are then 0.008T, 0.0048T and 0.0058T, where $T=H/U_p$. The mean data was collected along one line. The averaging was done over the plane. After turbulence had been fully developed, averaging was conducted over at least 200 flow-through time.

We use $\lambda_2$ criterion to identify vortices in our study instead of vorticity contour plot. Figure 2 has compared the DDES-M and LES-F $\lambda_2$ contour plots, it is clearly seen the vortices scales are abundant in LES-F, but DDES-M suffers the same problem as LES-M (not shown here) with grids being not fine enough to produce all the turbulence scales.

![Figure 2. $\lambda_2$ contour plots of DDES and LES.](image)

Figure 3. The dimensionless velocity profiles.
Figure 4. The rms fluctuations of \( \overline{u' u'_r} / U_b \) (Figures 4 (a), (b), (c)), and The kinetic energy normalized by the shear velocity \( k/ \overline{u'_r}^2 \) (Figure 4 (d)).

The dimensionless velocity profiles are shown in Figure 3. All simulations do not predict as proper logarithmic region as LES-F does, although LES-F does show some small offset to the reference DNS result. The log-layer mismatch is not obvious in DES and DDES in all grids, but DDES does not improve the results, comparing with DES and LES. Note also, results of DDES and DES with coarse grids are much more unstable than LES-C. The results do not show that being used as wall-function, DDES and DES will be better than LES with no wall function.

Figure 4 show the resolved rms fluctuations; \( ( \overline{u' u'_r} )^{1/2} / U_b \), and the kinetic energy normalized by the shear velocity, \( k/ \overline{u'_r}^2 = ( \overline{u' u'_r} / 2 )/ \overline{u'_r}^2 \). The computations with the coarse and the medium grid (DDES-C, DES-C, LES-C and DDES-M, DES-M, LES-M) overpredict the peak of the kinetic energy as shown in Figure 4 and underpredict the wall stress. The reason for this is likely an inadequate grid resolution. If the near-wall flow structures are not properly resolved, the effective shear stress on the wall is reduced. This is also the case of DES-C and DDES-C, the fluctuations normal to the wall (vrms) are underpredicted, as shown in Figure 4, even worse than LES-C, which decreases the momentum transfer between the wall and the core flow. The dominant streamwise fluctuations (urms) grow and so does the resolved turbulent kinetic energy. The fine-grid simulation LES-F predicts all the monitored quantities quite well, so it probably catches most of the eddies present in the flow. In this case, the largest deviations of the turbulent fluctuations are located in \( \nu/H=0.12 \), when compared to the DNS results. It is probably because the stretching need to be lowered so as to increase the near-wall
grids number. We cannot see from the results that DDES and DES works better than those cases without wall-function, instead we have found 1) unstable behaviour, 2) even worse results than LES without wall function. Though from the gridding point, coarse grids meet best the need for a true DDES and DES, but the current results is far from satisfactory.

Conclusions

A more complete study would be comparing different Reynolds numbers from low ones to high ones, but it's beyond our focus here, the behaviours in high Reynolds number are quite different from lower ones in authors' knowledge, which can not be stated in this paper.

We would draw some conclusion from the above research,

1. Insufficient grid resolution will lose in capturing the near-wall turbulent structures and then the lower wall shear stresses are predicted, this is the case of all three turbulent modeling approaches, namely LES, DES and DDES;
2. DES, and its revision DDES, which is primarily configured for outside layer matching, does not perform as a wall-function modeling of LES, especially at low Reynolds numbers. The main issue is not a question of log-layer mismatch, but some unsatisfactory and unstable results.

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Reference


