Assessment of two approaches to accelerate RANS to LES transition in shear layers in the framework of ANSYS-FLUENT

E K Guseva, M S Gritskevich, A V Garbaruk

Peter the Great St. Petersburg Polytechnic University, 29 Polytechnicheskaya str., 195251, St. Petersburg, Russia
E-mail: katia.guseva@inbox.ru

Abstract. An assessment of two approaches aimed at acceleration of the RANS-LES transition in separated flows has been performed in the framework of Delayed Detached Eddy Simulation (DDES). The former approach is based on the use of the shear-layer adapted subgrid scale (DDES$_{\Delta SLA}$) and the latter involves an alternative subgrid model ($\sigma$-DDES). Simulations of two separated flows, namely the backward-facing step flow and flow over a wall-mounted hump have been performed with the use of ANSYS-FLUENT. The results were compared with those obtained with the use of the in-house NTS code and with experimental data. It is shown that both RANS-LES acceleration techniques implemented in ANSYS-FLUENT allow more accurate and less code-sensitive results to be obtained in comparison to the original DDES formulation.

1. Introduction

Nowadays, hybrid RANS-LES approaches for turbulence modelling are considered as a compromise between the high accuracy of Large Eddy Simulation (LES) in separated flow regions and the low computational costs of methods based on the Reynolds Averaged Navier-Stokes equations (RANS). One of the most widely used approaches of this type is Detached Eddy Simulation (DES) [1] and its enhanced modifications. These methods are acknowledged as powerful tools in computational fluid dynamics and can be used in a wide range of applications.

Several modifications of DES aimed at acceleration of three-dimensional turbulent structure formation due to development of the Kelvin-Helmholtz instability in separated shear layers have been recently proposed [2],[3]. It has been shown [2],[3],[4] that such techniques lead to significant improvement of the results for separated flows. These modifications, however, have been implemented and tested only with the use of in-house codes, including NTS code [5], in which high-order low dissipation schemes are used. The results of eddy-resolving simulations and the development of the Kelvin-Helmholtz instability in shear layers depends on the discretization scheme [6], and thus the high dissipation of numerical schemes typically employed in commercial general purpose CFD codes can influence the efficiency of these enhanced approaches.

Therefore, the principal goal of the current paper is to assess the accuracy of the above mentioned techniques for the RANS-LES transition acceleration in the general purpose CFD code ANSYS-FLUENT [7]. For that purpose, these two approaches, namely an approach based on the substitution of the standard sub-grid length scale with that adapted to shear-layers ($\Delta_{SLA}$) [2] and an approach using an alternative sub-grid model [3] ($\sigma$-model) coupled with Delayed DES (DDES) [8] based on the Shear
Stress Transport (SST) model [9] are implemented in ANSYS-FLUENT. The obtained results are compared with experimental data and with those of the NTS [5] code.

2. Considered approaches to accelerate RANS-LES transition in shear layers

2.1. SST DDES combined with shear layer adapted sub-grid scale (DDES $\Delta_{SLA}$)

A detailed outline of the physical background of this model can be found in [2]. The key ingredient of the model is the sub-grid length-scale, which reads as:

$$
\Delta_{SLA} = \Delta_{\omega} \cdot F_{KH} \langle VT M \rangle
$$

Here $\Delta_{\omega}$ is the sub-grid length scale accounting for high anisotropy of the grids in initial regions of shear layers by excluding the size of the grid edge aligned with the vorticity vector [3] and $F_{KH}$ is an empirical function aimed at additional reduction of the subgrid length-scale defined as follows:

$$
F_{KH} = \begin{cases} 
1, & f_d < 0.99 \\
\max(0.1, \min(1.0, 0.1 + 6 \cdot \langle VT M \rangle - 0.15)), & f_d \geq 0.99 
\end{cases}
$$

$$
\Delta_{\omega} = \frac{1}{\sqrt{3}} \max([I_n - I_m])
$$

Here, $I_\omega = n_\omega \times r_\omega$, $n_\omega$ is the unit vector aligned with the vorticity vector, $r_\omega$ is the radius-vector of the $n$-th vertex of the considered grid cell, $f_d$ is the shielding function of DDES [8]. The argument of the $F_{KH}$ function is the Vortex Tilting Measure (VTM), which is a kinematic parameter used to identify quasi-2D regions of the flow:

$$
VT M = \frac{\sqrt{6} |(\dot{S} \cdot \omega) \times \omega|}{\omega^2 \sqrt{tr(S^2) - [tr(\dot{S})]^2}}
$$

$\dot{S}$ is the strain rate tensor, $tr( )$ denotes the trace operation, and $\omega$ is the vorticity vector averaged over the current and closest neighbouring cells. It should be mentioned, that averaged over the current and neighbouring cells VTM quantity, denoted by $\langle VT M \rangle$, is close to zero in quasi two-dimensional regions of the flow, whereas in regions with fully developed turbulence it is about 0.3 and higher. The shear layer adapted length-scale $\Delta_{SLA}$ simply replaces the original length scale $\Delta_{max}$ in the definition of the hybrid length scale of DDES. This substitution ensures reduction of the length scale in the initial part of separated shear layers leading to a strong drop of the eddy viscosity, which then unlocks the Kelvin-Helmholtz instability.

2.2. SST $\sigma$-DDES approach

Modification of the sub-grid model aimed at acceleration of the RANS-LES transition in separated shear layers for the DDES approach based on the $k-\omega$ SST turbulence model has been proposed in [10] based on the ideas of Mockett et. al. [3]. The subgrid model of SST $\sigma$-DDES performs as the algebraic $\sigma$-model [11] rather than as the Smagorinsky model.

The main difference between the SST $\sigma$-DDES and the original model is the substitution of the strain tensor invariant $S^2 = 2S_{ij}S_{ij}$ in the production terms of the turbulence kinetic energy and specific dissipation rate equations by the differential operator $S^2_{\sigma,DDES}$, which reads as follows:

$$
S^2_{\sigma,DDES} = S^2 - pos(f_d - 0.99) \cdot pos(L_{RANS} - L_{LES}) \cdot \left(S^2 - B_\sigma \cdot S_\sigma\right)
$$

Here, $L_{RANS}$ and $L_{LES}$ are respectively the RANS and LES length scales of DDES, $f_d$ is the shielding function of DDES [8], $C_{DES}$ is the DES constant [12], $B_\sigma = 57$ is the empirical constant calibrated based on simulations of the decay of isotropic homogeneous turbulence and operators $pos(a)$ and $S_\sigma$ are defined as follows:
3. Flows under consideration, computational setups, and numerics

3.1. Flow over a wall-mounted hump

This flow (the so-called 2D NASA wall-mounted hump) is experimentally studied in [13]. The Reynolds number based on the hump length \( c \) and reference velocity \( U_0 \) (maximum free stream velocity at the inlet of the domain) is \( Re = 9.36 \times 10^3 \), whereas the height of the hump is \( h = 0.128c \).

The computational domain and grid are shown in Figure 1. The grid has 510 and 126 cells in \( x \)- and \( y \)-directions respectively. The size of the domain in the spanwise direction is 0.4\( c \) and the grid-step is \( \Delta z = 5\times10^3 c \) resulting in a total grid size of about 5.0\( \times10^9 \) cells. The time step in the simulations is 0.001\( c/U_0 \), which ensures the CFL number is less than one in the entire domain.

![Figure 1. The computational domain and grid in XY-plane (every other grid line is shown)](image)

3.2. Backward-facing step

The Backward-Facing Step (BFS) flow [14] is a flow in the plane channel with a straight upper wall and a step on the lower wall with the channel expansion ratio of 5/4. The experimental Reynolds number based on the step height \( H \) is \( Re_H = 28000 \). The grid used consists of about 2.5 million cells. The XY-plane of the grid is shown in Figure 2. The grid clusters towards the walls and near the step. The size of the domain in the spanwise direction is 4\( H \) with a spanwise grid step of \( \Delta z = 0.05H \). The time step in the simulation is equal to 0.02\( H/U_0 \) ensuring the CFL number is less than one.

![Figure 2. The computational domain and grid in XY-plane](image)

3.3. Numerics used in the simulations

The considered versions of the DDES approach, described in Section 2, are implemented in ANSYS-FLUENT [7] codes using User Defined Functions (UDF).

In ANSYS-FLUENT the governing equations are written in the transient formulation for the incompressible fluid and solved with the use of the SIMPLEC method [15]. The pressure is interpolated with the use of “Standard” scheme [16] and for velocity the second-order bounded central difference scheme [17] is used. Gradients are calculated at cell centers with the use of the Green-Gauss theorem [18]. Time derivatives are calculated with the use of the three-layer second-order backward difference scheme [18]. Finally, the discrete equations are iteratively solved with the use of
the implicit point Gauss-Seidel method in conjunction with the algebraic multi-grid approach (10 sub-
iterations are employed for each time step).

The most pronounced difference between ANSYS-FLUENT and the in-house code NTS is in
approximation of the inviscid fluxes in the LES zones (fourth-order central-difference in NTS and
second-order bounded central-difference in ANSYS-FLUENT), or in other words, in the dissipative
properties of the schemes, which have significant influence on the development of the Kelvin-
Helmholtz instability in shear layers and, therefore, could result in noticeably different performance of
the considered DDES versions.

4. Results of the simulations

Figures 3 and 4 present visualizations of the considered flows obtained with different DDES versions.
It could be seen, that similarly to NTS code, usage of the methods for RANS-LES transition
acceleration in the framework of ANSYS-FLUENT leads to more rapid development of turbulent
structures in the separated shear layer and to resolution of finer eddies in the recirculation zone, which
could be seen in the results of both computational codes. Note however, that the fourth-order centered
scheme of NTS code allows resolving slightly smaller structures than the second-order bounded
central difference scheme of ANSYS-FLUENT.

Another important observation is the relatively high sensitivity of the original DDES approach to
the code numerics, which is observed for both flows considered (the difference is slightly more
pronounced for the backward facing step). In contrast, the modified DDES versions seem to be much
less sensitive to peculiarities of the employed numerical schemes and yield almost identical results in
both codes considered.

![Figure 3](image1.png)

**Figure 3.** Contours of the vorticity magnitude for the wall-mounted hump flow

![Figure 4](image2.png)

**Figure 4.** Contours of the vorticity magnitude for the backward facing step flow

A significantly better agreement between the computed and experimental data is observed in both
codes due to the using of the methods for acceleration of the turbulent structure formation. Indeed, as
could be seen from distributions of the mean skin friction coefficient (Figures 5, 6), the length of the
recirculation zone predicted by the enhanced DDES versions is in substantially better agreement with the experimental data compared to the standard one.

Moreover, mean results of the enhanced DDES versions are found to be less dependent on the numerics employed in the CFD code compared to the results of the original one, which agrees with the previous conclusions made from the instantaneous vorticity contours. Particularly, the longer RANS-LES transitional region observed in the standard DDES results is caused by the high dissipation of the ANSYS-FLUENT second-order bounded central difference scheme leading to accuracy deterioration in comparison to the NTS code.

The above mentioned trends could be also seen from figures 7, 8 where the resolved velocity fluctuations are depicted. Particularly, a delay in the formation of the three-dimensional structures is observed for DDES, which, in addition, highly depends on the employed numerical schemes, whereas similar results are obtained for enhanced DDES versions in both codes considered.

Conclusions
Simulations of two separated flows have been performed with the use of DDES combined with approaches aimed at acceleration of RANS-LES transition in separated shear layers. The results indicate that usage of such enhanced DDES versions within the ANSYS-FLUENT code allows significantly better agreement with both the experimental data and the results of NTS code to be obtained. Therefore, these approaches can be recommended for use within general purpose CFD codes.
Acknowledgments
The results of the work are obtained with the use of the computational resources of Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (http://www.spbstu.ru).

References
[1] Spalart P R, Jou W-H, Strelets M and Allmaras S R 1997 Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach Proceedings of first AFOSR international conference on DNS/LES (Ruston, Louisiana, USA) pp 137–47
[2] Shur M L, Spalart P R, Strelets M K and Travin A K 2015 An enhanced version of DES with rapid transition from RANS to LES in separated flows Flow Turbul. Combust. 95 709–37
[3] Mockett C, Fuchs M, Garbaruk A, Shur M, Spalart P, Strelets M, Thiele F and Travin A 2015 Two non-zonal approaches to accelerate RANS to LES transition of free shear layers in DES Notes Numer. Fluid Mech. Multidiscip. Des. 130 187–201
[4] Guseva E K, Garbaruk A V and Strelets M K 2017 Assessment of Delayed DES and Improved Delayed DES Combined with a Shear-Layer-Adapted Subgrid Length-Scale in Separated Flows Flow, Turbul. Combust. 98 481–502
[5] Shur M L, Strelets M K and Travin A K 2004 High-Order Implicit Multi-Block Navier-Stokes Code: Ten-Year Experience of Application to RANS/DES/LES/DNS of Turbulence https://cfd.spbstu.ru//agarbaruk/doc/NTS_code.pdf
[6] Kok J C and Ven H Van Der 2012 Capturing free shear layers in hybrid RANS – LES simulations of separated flow
[7] Mathur S R and Murthy J Y 1997 A pressure-based method for unstructured meshes Numer. Heat Transf. 32 195–215
[8] Spalart P R, Deck S, Shur M L, Squires K D, Strelets M K and Travin A 2006 A New Version of Detached-eddy Simulation, Resistant to Ambigious Grid Densities Theor. Comput. Fluid Dyn. 20 181–95
[9] Menter F R 1994 Two-equation eddy-viscosity turbulence models for engineering applications AIAA J. 32 1598–605
[10] Guseva E K, Garbaruk A V and Strelets M K 2017 Development and testing of σ-DDES approach based on k-ω SST turbulence model Therm. Process. Eng. 9 434–40 [in russian]
[11] Nicoud F, Toda H B, Cabrit O, Bose S and Lee J 2011 Using singular values to build a subgrid-scale model for large eddy simulations Phys. Fluids 23 1–12
[12] Gritskевич M S, Garbaruk A V., Schutze J and Menter F R 2012 Development of DDES and IDDES formulations for the k-w shear stress transport model Flow, Turbul. Combust. 88 431–49
[13] Greenblatt D, Paschal K B, Chung-Sheng Y and Harris J 2005 A Separation Control CFD Validation Test Case Part 2. Zero Efflux Oscillatory Blowing AIAA Pap. 2005-0485 1–24
[14] Vogel J C and Eaton J K 1985 Combined Heat Transfer and Fluid Dynamic Measurements Downstream of a Backward-Facing Step J. Heat Transfer 107 922–9
[15] Patankar S V. 1980 Numerical Heat Transfer and Fluid Flow
[16] Rhie C M and Chow W L 1983 Numerical Study of the Turbulent Flow Past an Airfoil with Trailing Edge Separation AIAA J. 21 1525–32
[17] Jasak H, Weller H G and Gosman A D 1999 High resolution NVD differencing scheme for arbitrarily unstructured meshes Int. J. Numer. Methods Fluids 31 431–49
[18] Kim S E, Mathur S R, Murthy J Y and Choudhury D 1998 A reynolds averaged Navier-Stokes solver using unstructured mesh-based finite-volume scheme AIAA Pap. 98–0231