Application of DDES and IDDES with shear layer adapted subgrid length-scale to separated flows

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Abstract. A comparative study is conducted of the original versions of Delayed Detached-Eddy Simulation (DDES) and Improved DDES (IDDES) and these approaches combined with “shear-layer-adapted” (SLA) subgrid length-scale proposed recently for resolving the issue of delayed RANS-to-LES transition in separated shear layers in global hybrid RANS-LES approaches. Computations were carried out of two separated flows: a transonic flow past M 219 cavity and a subsonic flow over NASA wall mounted hump. Results of the computations suggest that the use of the SLA subgrid length-scale considerably accelerates transition to resolved three-dimensional turbulence in the separated shear layers and substantially improves agreement with the experimental data.

1. Introduction

Hybrid RANS-LES approaches to turbulence modeling combine high quality of Large Eddy Simulation (LES) in separated flow regions and low computational costs of the methods based on the Reynolds Averaged Navier-Stokes equations (RANS) in the near wall regions of the flow. However near the boundary between RANS and LES regions (so-called “gray area”), where the solution is not either pure RANS or LES, accuracy of the hybrid approaches decreases. One of the examples is a tangible delay of formation of developed three-dimensional turbulent structures in separated shear layers typical of global hybrid methods like DES [1], which decreases quality of the solution not only in the shear layer but in the whole flow as well.

A remedy for this flaw has been suggested in a recent publication of Shur et al. [2], who proposed a new “shear-layer-adapted” (SLA) definition of the subgrid length-scale for global hybrid RANS-LES methods. Based on a set of numerical examples, it has been shown that replacing the standard DES definition of the subgrid length-scale (maximum local grid spacing) by the newly proposed one, $\Delta_{SLA}$, ensures a rapid unlocking of the Kelvin – Helmholtz (KH) instability and significant acceleration of transition to the developed turbulence in free and separated shear layers. The present work is aimed at evaluating efficiency of the DDES [3] and IDDES [4] approaches combined with the SLA subgrid length-scale and at finding out whether any undesirable side effects caused by interaction of this length-scale with the empirical functions involved in formulations of DDES and IDDES takes place.

2. Shear-layer adapted subgrid length-scale and its incorporation into the DDES and IDDES approaches

A detailed outline of the physical background of the new subgrid length-scale definition is presented in [2]. The definition reads as:
\[ \Delta_{SLA} = \tilde{\Delta}_o F_{KH} \left( < VTM > \right) \] (1)

Here \( \tilde{\Delta}_o = \frac{1}{\sqrt{3}} \max_{n,m=1,3} \left\| I_n - I_m \right\| \), where \( I_n = n_\omega \times r_n \), \( n_\omega \) is the unit vector aligned with the vorticity vector, and \( r_n \) is the radius-vector of the \( n \)-th vertex of the considered grid cell. This quantity takes into account high anisotropy of the grids typically used in initial regions of the shear layers and, in particular, excludes a control of both maximum and minimum grid steps in these regions.

The second ingredient of the new length-scale (1) is the empirical function \( F_{KH} \), aimed at additional reducing of the subgrid length-scale in the initial regions of the shear layers. The argument of this function, a kinematic parameter \( VTM \), is used to identify quasi-2D regions of the flow. It is defined as follows:

\[ VTM = \frac{\sqrt{6} | (\hat{S} \cdot \omega) \times \omega |}{\omega^2 \sqrt{3tr((\hat{S})^t - [tr(\hat{S})])^2}}. \] (2)

where \( \hat{S} \) is the strain rate tensor, \( tr(\cdot) \) denotes the trace operation, and \( \omega \) is the vorticity vector.

The quantity denoted by \( < VTM > \) in (1) is the VTM averaged over the current and closest neighboring cells. It is close to zero in quasi-2D regions of the flow, whereas in regions with fully developed turbulence it is about 0.3 and higher. This property of \( < VTM > \) allows constructing the following non-dimensional empirical function:

\[ F_{KH} \left( < VTM > \right) = \max \{ F_{KH}^\text{min}, \min \{ F_{KH}^\text{max}, F_{KH}^\text{min} + \frac{F_{KH}^\text{max} - F_{KH}^\text{min}}{a_2 - a_1} ( < VTM > - a_1 ) \} \}, \] (3)

where \( F_{KH}^\text{max} = 1.0 \) and the empirical constants are: \( F_{KH}^\text{min} = 0.1 \), \( a_1 = 0.15 \), \( a_2 = 0.3 \).

As seen from (3), in the flow regions where \( < VTM > \) is less than 0.15, the function \( F_{KH} \) is equal to 0.1, thus ten times reducing the length-scale \( \Delta_{SLA} \) compared to \( \tilde{\Delta}_o \). On the other hand, if \( < VTM > \) is higher than 0.3, the function equals 1.0, i.e., is not active.

In the inviscid flow areas and inside the attached boundary layers with no turbulent content the \( F_{KH} \) function should be deactivated as well.

For the inviscid regions, this is achieved by multiplying \( < VTM > \) by the quantity

\[ \max \left\{ 0.2\nu, \frac{1}{\max\{v_i - v_{i,v}, 10^{-6} v_{i,v} \}} \right\}. \]

As far as the attached boundary layer regions are concerned, in the framework of DDES the function \( F_{KH} \) is modified as [2]:

\[ F_{KH}^\text{lim} = \begin{cases} 1.0, & \text{if } f_d < (1 - \varepsilon) \\ F_{KH}, & \text{if } f_d \geq (1 - \varepsilon) \end{cases}, \] (4)

where \( f_d \) is the delay function of the DDES approach and \( \varepsilon = 0.01 \) is the empirical constant.

For the IDDES, based on the same ideas, we define the function \( F_{KH}^\text{lim} \) as follows:

\[ F_{KH}^\text{lim} = \begin{cases} 1.0, & \text{if } \tilde{f}_d > \varepsilon \\ F_{KH}, & \text{if } \tilde{f}_d \leq \varepsilon \end{cases}, \] (5)

where \( \tilde{f}_d \) is the analog of the delay function in IDDES.

Within the DDES approach, the new length-scale \( \Delta_{SLA} \) simply replaces the original definition \( \Delta = \Delta_{\text{max}} \). The modification of the IDDES approach is not as straightforward and implies only a partial replacement of \( \Delta_{\text{max}} \) with \( \Delta_{SLA} \) in the original IDDES definition of the subgrid length-scale. Namely, the original definition \( \Delta = \min \{ \max\{C_w d_w, C_n \Delta_{\text{max}}, \Delta_{zw} \}, \Delta_{SLA} \} \) should be replaced with
\[ \Delta = \min\{\max\{C_n d_w, C_n \Delta_{\text{max}}\}, \Delta_{\text{wn}}\} \], where \( C_n = 0.15 \) is an empirical constant and \( \Delta_{\text{wn}} \) is the wall-normal grid step.

3. Results and discussion
In this section we present computational set-ups and results of simulations of two test-cases chosen for evaluation of performance of modified (based on SLA subgrid length-scale) version of the DDES and IDDES approaches with Spalart-Allmaras background RANS model. All the simulations are carried out with the use of the NTS code which details are outlined in [5].

3.1. Transonic \( M = 2.19 \) cavity flow
This flow studied in the experiments [6] has the Mach number \( M = \frac{U_0}{a} = 0.85 \) and Reynolds number \( \text{Re} = \frac{H U_0}{\nu} = 3.4 \times 10^5 \), where \( U_0 \) is a free stream velocity and \( H \) is a quarter of the cavity depth. A quality of resolution of the shear layer separated from the leading edge of the cavity has a strong impact on the flow, in general, and on its unsteady characteristics, in particular, the latter being of crucial importance for an accurate prediction of the noise generated by the cavity. Therefore, this flow seems to be a good test case for evaluation of performance of the SLA subgrid length-scale.

The cavity is made in a flat plate and has the length of \( 20H \), height of \( 4H \). Its drawing and computational domain and grid with 3 million nodes used in the simulations are presented in Fig. 1. The grid clusters in the vicinity of the cavity walls and the shear layer which separates from the cavity leading edge. The time step in the simulations was equal to \( 2.5 \times 10^{-2} \frac{H}{U_0} \).

![Figure 1. Drawings of the cavity and computational domain and grid used in simulations](image)

Figures 2, 3 present instantaneous eddy viscosity and vorticity fields from the DDES computations with the use of the original and SLA subgrid length-scales. They clearly show that consistently with the design of the SLA length-scale, it leads to a tangible reducing of the turbulent viscosity compared to the original definition (see Fig. 2) which, in turn, leads not only to unlocking of the KH instability and accelerating transition to 3D turbulence in the shear layer but also to somewhat finer resolution of the turbulent structures inside the cavity (see Fig. 3). As a result, predicted sound pressure level and power spectra of the pressure fluctuations on the cavity floor turn out to be considerably closer to the experimental data than those of the standard DDES, the spectra improvement being quite pronounced in terms of both the broadband part level and frequencies of the tones (Fig. 4).

![Figure 2. Snapshots of eddy viscosity obtained with the original and modified DDES versions](image)
Figure 3. Snapshots of vorticity magnitude obtained with the original and modified DDES versions

Figure 4. Sound pressure level and power spectra of pressure fluctuations on the cavity floor predicted by original and modified DDES versions

Similar but even more pronounced tendencies are observed in the results of IDDES of the considered flow. Namely, the modified IDDES version predicts more rapid roll-up of the separated shear layer (Fig.5) which leads to a more accurate prediction of the unsteady pressure characteristics on the cavity flow (Fig.6).

Figure 5. Snapshots of vorticity magnitude predicted by original and modified IDDES versions

Figure 6. Sound pressure level and power spectra of pressure fluctuations on the cavity floor predicted by original and modified IDDES versions

3.2. Flow over the wall mounted hump

This is a flow over a so called 2D NASA wall-mounted hump which was studied in the experiments [7]. The Reynolds number based on the hump length, \( c \), and reference velocity, \( U_0 \) (maximum free stream velocity at the inlet of the domain) in the experiment was equal to \( 9.36 \times 10^5 \), and the height of the hump, \( h \), was equal to 0.128 \( c \).

A computational domain and a grid in XY-plane used in the simulations are shown in Fig.7. The grid has 510 and 126 cells in the \( x \) - and \( y \)-directions, respectively. A size of the domain in the homogeneous, \( z \), direction is 0.4 \( c \), and the grid-step, \( \Delta z \), is uniform and equal to \( 5 \times 10^{-3}c \). The total grid size is about 5 Million. A time step in the simulations is equal to \( 2 \times 10^{-3}c/U_\infty \).
Figures 8-10 present primary results of the DDES computations of this flow. As seen in Figs. 8, 9 where instantaneous fields of turbulent viscosity and vorticity magnitude are depicted, the standard DDES suffers from a strong delay of transition to resolved 3D turbulence in the separated shear layer, whereas the use of the SLA subgrid length-scale reduces the turbulent viscosity, unlocks the KH instability in the shear layer, and accelerates the transition. As a result, mean characteristics of the flow, e.g., skin friction predicted by the modified DDES version better agree with the experimental data than those of the standard DDES (Fig. 10).

Figure 8. Snapshots of eddy viscosity obtained with the original and modified DDES versions

Figure 9. Snapshots of vorticity magnitude obtained with the original and modified DDES versions

Figure 10. Mean friction coefficient distributions. Comparison of results obtained with the original and modified DDES versions and experimental data

In general, similar results are obtained with the use of IDDES approach. However, as seen from the comparison of vorticity snapshots obtained with the use of the original versions of DDES and IDDES (left frames in Figs. 9 and 11), the latter suffers from the delay of the RANS-to-LES transition in the separated shear layer not as severely as the former. Not surprisingly, the effect of the modification of the subgrid length-scale in the original IDDES also is not as pronounced as in the original DDES. For instance, the skin friction coefficients predicted by the original and modified version of IDDES are virtually identical and very well agree with the experimental data (Fig. 12). Nevertheless, the use of the SLA subgrid length-scale in the framework of IDDES still turns out to be helpful: it somewhat speeds the shear layer roll up (Fig. 11) which results in a corresponding improvement of the agreement with the experiment on the normal Reynolds stresses in the vicinity of separation (Fig. 13).

Figure 11. Snapshots of vorticity magnitude obtained with the original and modified IDDES versions
Conclusions
A numerical study was conducted focused on testing of DDES and IDDES approaches combined with a recently proposed shear-layer-adapted subgrid length-scale. Two separated flows were considered: a flow with a fixed separation (transonic flow past M 219 cavity) and a flow with smooth-surface separation and reattachment (NASA wall-mounted hump). Results of the simulations show that shear-layer-adapted versions of both approaches surpass the original ones in terms of agreement with the experiments which is achieved thanks to a more rapid transition from RANS to LES in the separated shear layers. No negative side effects caused by a possible interaction of the solution-dependent length-scale with the empirical functions involved into the original DDES and IDDES formulations were observed.

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