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Application of Shear Layer Adapted Sub-grid Length Scale in SST-IDDES

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Abstract: Shear layer adapted sub-grid length scale is applied in Improved Delayed Detached Eddy Simulation with SST background RANS model (SST-IDDES). The objective is to ease the “grey area” through dramatically decreasing the eddy viscosity in the initial region of a free shear layer. Two test cases including a near-sonic jet and a backward-facing step flow are tested to show the advantage of the new solution-dependent definition of sub-grid length scale over the original one in unlocking the Kelvin-Helmholtz (K-H) instability in the free shear layer.
Keywords: SST-IDDES, Shear Layer Adapted Sub-grid Length Scale, Grey Area

1 Introduction

Hybrid Reynolds-Averaged Navier-Stokes (RANS) / Large Eddy Simulation (LES) methods in turbulence modeling combine the high fidelity of LES for separated flows and the low computational costs of RANS for turbulent boundary layer flows, of which Detached Eddy Simulation (DES) is a popular one of such hybrid methods. DES was first proposed by Spalart [1]. It is formulated as a modification to an existing RANS model by substituting the RANS length scale with a DES length scale. It performs as RANS in the turbulent boundary layer and LES in the separated flow region. However, it suffers from “grey area” issue in the RANS to LES switch showing as a severe delay of K–H instability. The delay is caused by the excessive eddy viscosity in the initial region of a free shear layer. Typically, the excessive eddy viscosity is due to the convection of the eddy viscosity from the upstream attached boundary layer modelled by RANS, as well as a too large sub-grid scale caused by the grid anisotropy (typically, coarse in streamwise and spanwise directions and fine in the wall normal direction). Shur et al. [2] proposed a shear layer adapted sub-grid length scale to increase the destruction of eddy viscosity and promote the RANS/LES switching. Initially, it was applied to DDES with SA background RANS model (SA-DDES). Later, Probst et al. [3] applied this length scale to DDES with SST background RANS model (SST-DDES) and evaluated its performance only in the NASA wall-mounted hump flow case.

In this paper, the shear layer adapted sub-grid length scale is developed for SST-IDDES and two fine-tunings are proposed to the length scale. In section 2, the standard SST-IDDES and the shear layer adapted sub-grid length scale [4], [5]are briefly introduced. The two fine-tunings to the length scale are also presented. In section 3, the new sub-grid length scale is applied to a near sonic jet and a backward-facing step flow. Finally, the conclusions are given in section 4.

2 Computational Methodology

2.1 Standard SST-IDDES Method

Standard IDDES method is obtained through substituting the RANS length scale with IDDES length scale in the destruction term of turbulent kinetic energy (TKE) transport equation. The TKE equation of SST-IDDES is

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho u_j k}{\partial x_j}=P_k-\frac{\rho k^{\frac{3}{2}}}{l_{IDDES}}+\frac{\partial}{\partial x_j}\left[\left(\mu+\sigma_k\mu_t\right)\frac{\partial k}{\partial x_j}\right], \tag{1}$$

where k is the modeled TKE. The IDDES length scale l_{IDDES} is defined as

$$l_{IDDES}=\tilde{f}_d\left(1+f_e\right)l_{RANS}+\left(1-\tilde{f}_d\right)l_{LES}, \tag{2}$$

where $\tilde{f}_d$ is a blending function and f_e is an elevation function. $l_{RANS}=\sqrt{k}/C_\mu w$ and $l_{LES}=C_{DES}\Delta$ are the turbulent length scale of RANS and the sub-grid length scale of LES respectively. C_{DES} is obtained by a blending of $C_{DES,k-\omega}$ and $C_{DES,k-\varepsilon}$ through $C_{DES}=F_1\times C_{DES,k-\omega}+\left(1-F_1\right)\times C_{DES,k-\varepsilon}$. $C_{DES,k-\omega}=0.78$ and $C_{DES,k-\varepsilon}=0.61$ are used in this paper. The grid scale Δ is defined as

$$\Delta=\min\left\{\max\left[C_w d_w,C_w\Delta_{\max},\Delta_{wn}\right],\Delta_{\max}\right\}, \tag{3}$$

where C_w is a constant 0.15, d_w is the distance to wall, $\Delta_{\max}$ and Δ_{wn} are the maximum edge length and the wall normal length of a cell. More details can be found in [4] and [5].

2.2 Shear Layer Adapted Sub-grid Length Scale and the Proposed Fine-tunings

To decrease the sub-grid length scale in the initial region of free shear layer, two modifications are included in the shear layer adapted sub-grid length scale. Firstly, vorticity-related sub-gird length scale is applied. Secondly, a detection function for quasi-2D flows is used to further drop the sub-grid length scale in the initial region of free shear layer. Consequently, the final sub-grid length scale reads as

$$\Delta_{SLA}=\Delta_\omega F_{KH}^{\lim}\left(VTM\cdot\max\left\{1,\frac{0.2\nu}{\max\left\{\left(\nu_t-\nu_{t,\infty}\right),10^{-6}\nu_{t,\infty}\right\}}\right\}\right). \tag{4}$$

The definition of the vorticity-related sub-grid length scale Δ_ω is [2]

$$\Delta_\omega=\frac{1}{\sqrt{3}}\max_{n,m=1,8}\left|\mathbf{n}_\omega\times\left(\mathbf{r}_m-\mathbf{r}_n\right)\right|, \tag{5}$$

where $\mathbf{r}_n$ $\left(n=1,...,8\right)$ is the locations of cell vertices and $\mathbf{n}_w$ is the unit vorticity vector. The $F_{KH}\left(VTM\right)$ function reads as

$$F_{KH}\left(VTM\right)=\max\left\{F_{KH}^{\min},\min\left\{F_{KH}^{\max},F_{KH}^{\min}+\frac{F_{KH}^{\max}-F_{KH}^{\min}}{a_2-a_1}\left(VTM-a_1\right)\right\}\right\}, \tag{6}$$

where $F_{KH}^{\max}=1.0$, $F_{KH}^{\min}=0.1$, $a_1=0.15$ and $a_2=0.3$. Vortex Tilting Measure (*VTM*) is a detection function for the quasi-2D flow regions. It is close to 0.0 for quasi-2D flows and 1.0 for fully 3D turbulent flows.

The application of Δ_{SLA} to IDDES formulation is by replacing the sub-grid length scale $\Delta=\min\left\{\max\left[C_w d_w,C_w\Delta_{\max},\Delta_{wn}\right],\Delta_{\max}\right\}$ with $\Delta=\min\left\{\max\left[C_w d_w,C_w\Delta_{\max},\Delta_{wn}\right],\Delta_{SLA}\right\}$ as in [6]. In addition, two fine-tunnings to Δ_{SLA} are proposed in this paper:

1) Removing $1/\sqrt{3}$ in the definition of Δ_ω in Eq. (5) to avoid numerical dissipation;

2) When computing Δ_ω by Eq. (5), only some of the edges and diagonals are projected to the plane normal to the vorticity in order to reduce the computational cost.

3 Results

In this section, two test cases are presented to demonstrate the advantage of Δ_{SLA} in the framework of SST-IDDES. Firstly, an axisymmetric near-sonic jet is simulated to show the advantage of Δ_{SLA} over $\Delta_{\max}$ as the sub-grid length scale of LES in SST-IDDES. Secondly, a wall-bounded backward-facing step flow is calculated and test the both DDES branch and WMLES branch of SST-IDDES.

3.1 Round Jet

An axisymmetric unheated near-sonic jet from a convergent nozzle is studied to show the advantage of Δ_{SLA} as the sub-grid length scale of LES calculation in SST-IDDES. The experiment was conducted by Bridges and Wernet [7]. The jet exit Mach number u_{jet}/a_{jet} is 0.985. Two sets of grid are employed. The total cell numbers are 6.5 million and 14.7 million for the coarse grid and fine grid respectively. The computational domain and boundary conditions are shown in Figure 1.

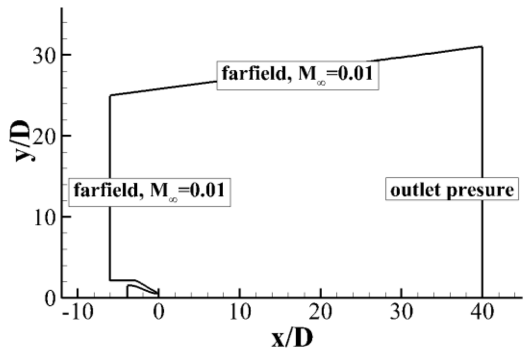
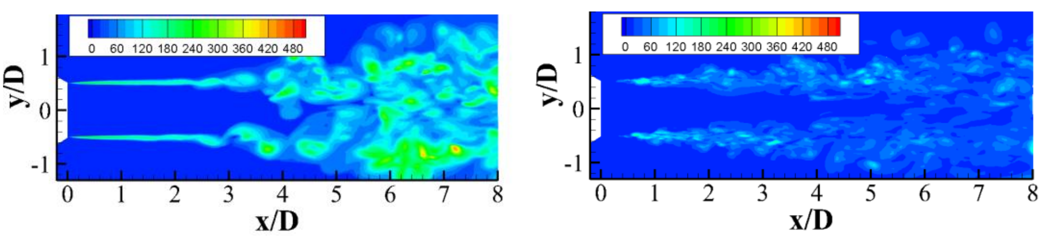
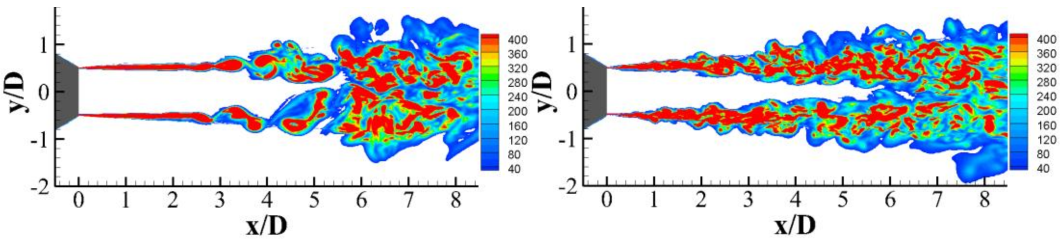


Figure 1 Computational domain and boundaries

Figure 2 compares the eddy viscosity and vorticity magnitude calculated from standard IDDES and IDDES with $\Delta = \Delta_{SLA}$. Compared with standard IDDES, the eddy viscosity computed by the IDDES with $\Delta = \Delta_{SLA}$ is much smaller in the initial region of the free shear layer due to a significant reduction of sub-grid length scale. Consequently, the switching from RANS to LES in the free shear layer is more rapid for IDDES with $\Delta = \Delta_{SLA}$ and more turbulent structures are resolved.



(a) standard IDDES (b) IDDES with $\Delta = \Delta_{SLA}$



(c) standard IDDES (d) IDDES with $\Delta = \Delta_{SLA}$

Figure 2 Instantaneous fields of eddy viscosity μ_t / μ (upper) and vorticity magnitude (lower) calculated from standard IDDES and IDDES with $\Delta = \Delta_{SLA}$ on the fine grid

3.2 Backward-facing Step

Figure 3 shows the computational domain and boundary conditions. The height of the channel upstream of the step is $4H$ and the expansion ratio is 5/4. The inlet flow speed is 11.3 m/s. The Reynolds number based on the inlet velocity U and the step height H is 28000. The experiment was conducted by Vogel and Eaton [8]. A coarse grid and a fine grid are employed. The corresponding cell numbers are 0.72 million and 1.44 million respectively.

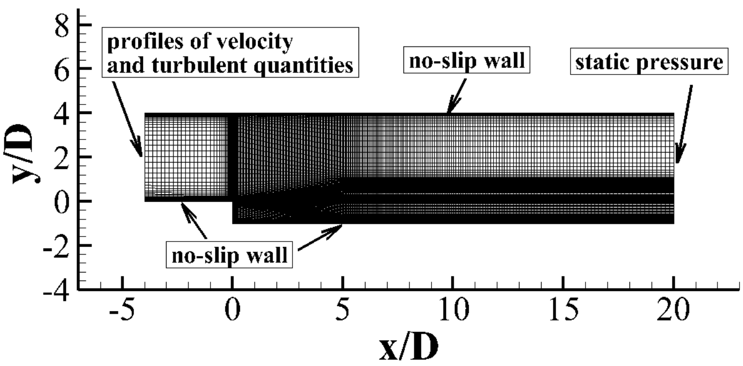
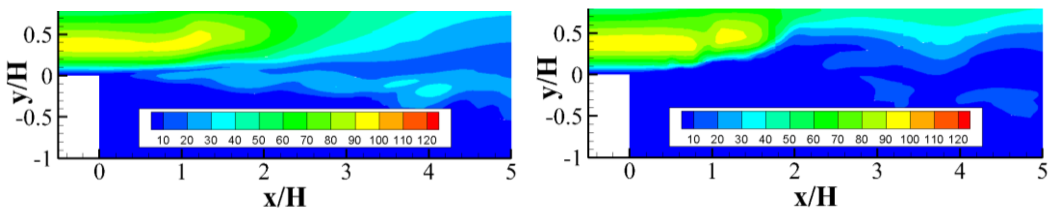
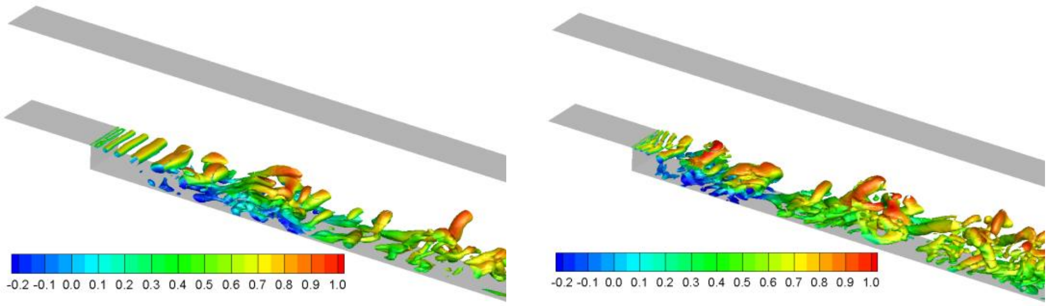


Figure 3 Computational domain and boundary conditions

Figure 4 shows the enlarged views of the instantaneous eddy viscosity in the separated shear layer. Compared with standard IDDES, IDDES with $\Delta = \Delta_{SLA}$ significantly reduces the eddy viscosity in the initial region of the free shear layer. It is very crucial to unlock the K-H instability of the free shear layer.



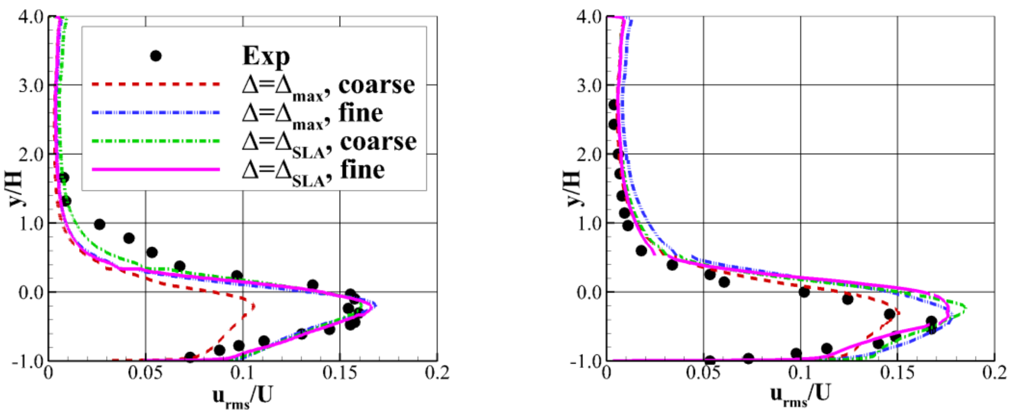
(a) standard IDDES (b) IDDES with $\Delta = \Delta_{SLA}$



(c) standard IDDES (d) IDDES with $\Delta = \Delta_{SLA}$

Figure 4 Instantaneous eddy viscosity (upper) and iso-surface $Q(H/U)^2 = 0.1$ (lower) on the coarse grid

Figure 5 shows the streamwise velocity fluctuations at two streamwise locations x/H=3.2 and x/H=4.5. The both locations are inside the separation bubble which locates downstream of the step. Compared with standard IDDES, the results from the IDDES with $\Delta = \Delta_{SLA}$ agree better with the experiment especially for the coarse grid. However, the standard IDDES first underestimates the fluctuations and then overestimates the fluctuations further downstream.



(a) *x/H*=3.2 (b) *x/H*=4.5

Figure 5 Streamwise velocity fluctuations at two streamwise locations from standard IDDES and IDDES with $\Delta = \Delta_{SLA}$

4 Conclusion

Shear layer adapted sub-grid length scale has been developed for SST-IDDES. The goal is to mitigate the “grey area” issue in the standard IDDES method. In addition, two fine-tunings are suggested. All the test cases have shown the superiority of IDDES with $\Delta = \Delta_{SLA}$ over standard IDDES in accelerating the switch from RANS to LES.

5 Acknowledgements

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