Aerospace Science and Technology 74 (2018) 46–55

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

An investigation of interface conditions inherent in detached-eddy simulation methods

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ARTICLE INFO

Article history:
Received 29 March 2017
Received in revised form 25 August 2017
Accepted 3 January 2018
Available online 3 February 2018

Keywords:
Detached-eddy simulation
Separated flow
Shielding function
Computational fluid dynamics

ABSTRACT

The interfaces where the RANS modeled areas match the LES resolved regions are comparatively investigated with regard to the four popular detached-eddy simulation (DES) variants; namely, one-equation Spalart–Allmaras (SA) and two-equations Menter's SST background DES methods (SA-DES and SST-DES), as well as their respective delayed versions (SA-DDES and SST-DDES). The comparisons are aimed at further interpretation of their performance differences under various flows. Although all four DES variants can consistently predict results in fully separated circular cylinder flow, the SST-DES interface is like the SA-DDES interface around the wall, which indicates that, in this case, the shielding function f_{d_cor} of SST-DDES is redundant. Moreover, the recalibrated f_{d_cor} for SST-DDES is found to preserve double the boundary-layer thicknesses in the flat-plate flow, and shown to be too conservative to resolve the unsteady vortex in the cavity-ramp flow. On the other hand, SA-DDES with the shielding function f_d shows an advantage by properly balancing the need of reserving the RANS modeled regions for wall boundary layers and generating the unsteady turbulent structures in detached areas.

1. Introduction

Although large-eddy simulation (LES) techniques are presumably more accurate than Reynolds averaged Navier–Stokes (RANS) approaches, the required computational cost for engineering separated flows is extremely high. Hybrid RANS/LES approaches [1] represent a promising option for improving the prediction of such flows at a reasonable cost, by taking into account most of the flow unsteadiness. The main idea of these methods is to model the turbulent structures in the attached flow region, and to solve the large length-scale structures in the other regions. One of the most popular RANS/LES methods is detached-eddy simulation (DES) proposed by Spalart et al. in 1997 (SA-DES) [2], and is based on a modification of the length scale employed by the Spalart–Allmaras (SA) model [3]. Strelets extended the definition of DES and claimed that the DES/SA link is not fundamental, and that other models could be built into DES concept. By this consideration, the Menter's SST model [4] was transformed into the DES mode by modifying the length scale of the k-transport equation in 2001 (SST-DES) [5]. However, a major issue with the use of a pure DES approach is that the interface between the RANS and LES regions depends greatly on grid spacing. A fine mesh with grid spacing much smaller than the boundary-layer thickness may locate the RANS/LES transition within the boundary layer. The premature switch to the LES mode will lead to insufficiently modeled Reynolds stresses, resulting in modeled stress depletion (MSD) and non-physical separation [6]. To alleviate this deficiency, Menter and Kuntz [7] used the blending functions F_1 or F_2 of the SST model to "shield" the boundary layer, by which they implied the "preserve RANS mode," or "delay LES function" in 2004 (SST-DDES). As a derivative of this proposal, Spalart et al. [8] proposed the SA-based delayed-DES in 2006 (SA-DDES), by constructing a generic shielding function f_d in order to detect the boundary-layer region and "preserve RANS mode". In turn, Gritskevich et al. [9,10] employed a modified f_d to consolidate a standard SST-DDES approach, since the blending function F_2 was considered relatively conservative.

Although more DES-like methods have emerged recently [11,12], DES and its delayed version (either SA or SST-based) are still most popular due to the ease of programming and confidence with regard to abundant validations. Nowadays, DES strategies are available in Computational Fluid Dynamics (CFD) codes including Cobalt, CFL3D, CFD++, STAR-CD, Acusolve, Fluent, etc. However, it appears that these software vendors provide publications and consultation to new DES users, rather than a comprehensive set of

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https://doi.org/10.1016/j.ast.2018.01.005
1270-9638/

instructions. In addition, variants of the DES model, such as SA and SST-based DES/DDES, have been introduced with rather different characteristics, which make model selection and results interpretation challenging. In the present study, three typical test cases, a boundary-layer flow, a classical circular cylinder flow and a more complex cavity-ramp flow, were simultaneously calculated by the above four DES methods. In particular, the interfaces between RANS and LES mode, which are inherent in each DES model, were illustrated and discussed. As a result of extensive simulations, we hope to learn more about the performance of DES strategies.

2. Brief description of DES strategies

2.1. SA-DES and DDES

The constructions of SA-DES and SA-DDES are based on the one-equation RANS model of Spalart–Allmaras (SA) [3]. For SA-DES, the turbulent length scale d_w of SA is replaced by a new DES length scale, which is given by

$$\widetilde{d} = \min(d_\mathrm{w}, C_\mathrm{DES}\Delta), \tag{1}$$

where $C_\mathrm{DES} = 0.65$ is the only new adjustable model constant, and Δ is based on the largest local grid spacing defined by $\Delta = \max(\Delta x, \Delta y, \Delta z)$. For wall-bounded separated flows, SA-DES functions as the standard RANS model in the attached boundary layer and as its subgrid scale model in detached flows [13]. The interface between the RANS and LES mode depends on Equation (1). That is, when $d_\mathrm{w} < C_\mathrm{DES}\Delta$, $\widetilde{d} = d_\mathrm{w}$, and the simulation is reduced to RANS mode. Otherwise, when $d_\mathrm{w} \geq C_\mathrm{DES}\Delta$, SA-DES exhibits the LES behavior.

However, SA-DES has an inherent shortcoming of possibly premature switching from RANS to LES mode within the boundary layer, caused by excessive mesh clustering. This can lead to unphysical outcomes, like the underestimation of skin friction [14]. In order to get rid of this drawback, Spalart et al. [8] proposed SA-DDES with a shielding function f_d, in order to identify the boundary layer and delay the switch. The formulation is as follows:

$$f_\mathrm{d} = 1 - \tanh\left([8r_\mathrm{d}]^3\right), \tag{2}$$

which equals to 0 in the boundary layer and increases to 1.0 at the edge. The parameter r_d is borrowed from the SA model with slight modifications, and can be referred in the previously cited literature. Then, the length scale of SA-DES is redefined by:

$$\widetilde{d} = d_\mathrm{w} - f_\mathrm{d}\max(0, d_\mathrm{w} - C_\mathrm{DES}\Delta). \tag{3}$$

For most applications, the region where $f_\mathrm{d} = 0$ covers the area where $d_\mathrm{w} < C_\mathrm{DES}\Delta$; therefore, the interface inherent in SA-DDES depends mostly on the distribution of the function f_d, as depicted by Equation (4):

$$f_\mathrm{d} = \begin{cases} 0, & \text{RANS mode,} \\ 0 < f_\mathrm{d} < 1, & \text{transition,} \\ 1, & \text{LES mode.} \end{cases} \tag{4}$$

2.2. SST-DES and DDES

The two-equation RANS model of Menter's SST4 is chosen as the base for the construction of SST-DES and SST-DDES. The model uses the parameter F_1 to switch from k–ω to k–ε, whose value is equal to 0 away from the surface (k–ε model), and switches over to 1 inside the boundary layer (k–ω model). In addition, F_2 is the second blending function and behaves similarly to F_1. The SST-DES modification replaces the turbulent length scale $l_{k-\omega}$ of SST by $\tilde{l} = \min(l_{k-\omega}, C_\mathrm{DES}\Delta)$. Since the SST model is based on the blending of k–ω and k–ε, Strelets5 calibrated the model by running both the k–ω and k–ε models on isotropic turbulence. This leads to a blending constant as expressed below

$$C_\mathrm{DES} = (1 - F_1) \times 0.61 + F_1 \times 0.78. \tag{5}$$

Table 1
The turbulent length scales in four DES methods.

Strategies	Turbulent length scale		
	RANS mode	Transition mode	LES mode
SA-DES	d_w	–	$C_\mathrm{DES}\Delta$
SA-DDES	d_w	$d_\mathrm{w} - f_\mathrm{d}\max(0, d_\mathrm{w} - C_\mathrm{DES}\Delta)$	$C_\mathrm{DES}\Delta$
SST-DES	$l_{k-\omega}$	–	$C_\mathrm{DES}\Delta$
SST-DDES	$l_{k-\omega}$	$l_{k-\omega} - f_\mathrm{d\_cor}\max(0, l_{k-\omega} - C_\mathrm{DES}\Delta)$	$C_\mathrm{DES}\Delta$

The interface between the RANS and LES mode in SST-DES depends not only on the grid size (as in SA-DES), but also on the calculated turbulence variables K and ω. In a sense, the utilization of local turbulence properties provides additional control in specifying the flow regions intended for each mode, and, thereby it removes much of the burden from the grid-generation process.

For fine grids, the switch from RANS to LES mode was found to take place somewhere inside the boundary-layer, where it produced a premature (grid-induced) separation. In order to reduce grid influence, the original SST-DDES was proposed with the help of the underlying zonal formulation of the SST model. The turbulent length scale $l_{k-\omega}$ was replaced by $\tilde{l} = \min(l_{k-\omega}, C_\mathrm{DES}\Delta/(1 - F_\mathrm{SST}))$ with $F_\mathrm{sst} = F_1$ or F_2 [7]. However, F_sst was assessed as too conservative to resolve the turbulence in detached flow regions that were not sufficiently removed from walls. Gritskevich et al. [9,10] modified the empirical constants of Equation (2), and consolidated the SST-DDES approach with the length scale as:

$$\tilde{l} = l_{k-\omega} - f_\mathrm{d\_cor}\max(0, l_{k-\omega} - C_\mathrm{DES}\Delta), \tag{6}$$

in which the shielding function of SA-DDES is modified as

$$f_\mathrm{d\_cor} = 1 - \tanh\left([20r_\mathrm{d}]^3\right). \tag{7}$$

Note that, unlike the interface condition of SA-DDES, the shielding function $f_\mathrm{d\_cor}$ could only decide the RANS modeled region near the wall. In the farfield, where $f_\mathrm{d\_cor} = 1$, the RANS and LES interface depends on the magnitude of $l_{k-\omega}$ and $C_\mathrm{DES}\Delta$.

As mentioned above, the turbulent length scales of the four DES methods are listed in Table 1. The two DES approaches would automatically choose the smaller one by comparing the length scales of the respective RANS and LES modes. DDES approaches may adopt a combination of length scales of two modes, where the value of the shielding function f_d lies in the range 0–1.

3. Numerical simulations and discussions

Three test cases were chosen to investigate the performance and interface conditions of the above mentioned DES methods. One is the flat plate boundary-layer flow with different grid resolutions, in order to demonstrate the MSD problem. The second is the classical circular cylinder flow at Reynolds number 3900, which is fully separated and considered to be the primary application of DES methods. Another one is the supersonic cavity-ramp flow at Mach number 2.92, which contains both the separated and attached regions. The last one is more common in engineering applications.

Simulations are performed using high-order structured code, which is a time-dependent, compressible Reynolds-averaged