Sixth HRLM Symposium, 26-28 September 2016, Strasbourg University, France

Session: Keynote

Stress-Blended Eddy Simulation (SBES) - A new Paradigm in hybrid RANS-LES Modeling

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Introduction

It is observed in many CFD simulations that RANS models show inherent technology limitations for certain types of flows (for example, flows with large/massive separation, flows with strong mixing zones, flows with strong interactions of different flows features). For this reason, there is an ongoing drive in the turbulence community to augment RANS capabilities by Scale-Resolving Simulation (SRS) methods. Motivated by the high cost of conventional Large Eddy Simulation (LES) and Wall Modelled LES (WMLES) for wall boundary layer simulations, hybrid RANS-LES models have been developed over the past two decades. The most prominent models are from the family of Detached Eddy Simulation (DES) variants proposed by Spalart [1]. The starting point for DES was the desire of utilizing LES in large separation zones and for free shear flows without being forced into the excessive grid- and time-step resolution requirements of LES for attached and mildly separated boundary layers. DES was therefore originally designed to cover all attached boundary layers in RANS mode and to only switch to LES mode in ‘detached’ regions.

In further steps DES was extended to also operate in Wall-Modelled LES (WMLES) format, where the RANS portion of the model is only active in the innermost part of the boundary layer and LES is applied over the rest of the domain. The savings in this mode are much smaller, as RANS only reduces the otherwise excessive near wall grid requirements of wall-resolved LES. The most prominent version capable of WMLES is IDDES [2] developed specifically for that purpose.

For industrial simulations, DES and variants (DDES, IDDES) have shown weaknesses in the following aspects:

- Shielding of boundary layers intended to be solved in RANS mode. As known, DES can lead to Grid-Induced Separation (GIS) when the mesh is refined in the boundary layer as the RANS model can be affected by the grid limiter without proper balancing between RANS and LES turbulence content.

- Slow 'transition' from RANS to LES in Separating Shear Layers (SSL). Conventional DES/DDES provides overly large values of eddy-viscosity in SSLs and therefore prevents their fast break-up into resolved turbulence. This is caused by the specific way the LES portion of DES is formulated.

In recent years more modern versions of DES have been developed, which address some of these deficiencies, most noticeably the model version [3].

However, in industrial CFD simulations, additional requirements arise. Over the years, many CFD users have voiced a desire for a more modular approach, whereby they could use a pre-selected RANS and another pre-selected LES model instead of the mix of both formulations within one set of equations. In many instances, industrial groups have used certain LES models (e.g. dynamic LES models in the combustion sector) and want to extend their simulation to include parts of the domain which can only be covered by RANS models (piping, blades, …). During that change, they don't want to switch their validated and trusted LES model. In addition, a frequently voiced user-request was to be able to clearly distinguish regions where the models run in RANS and regions where the model runs in LES mode. Finally, users prefer model formulations which can be run safely in 'DES-mode' with strong shielding but also in WMLES mode in regions of sufficient numerical resolution (and an upstream trigger into LES-mode). Stress-Blended Eddy Simulation (SBES) is an approach to cover all the above requirements.

As this paper represents an invited lecture to the conference on industrial aspects of turbulence modelling, only the basic principle of SBES can be provided. The details of the blending formulation are proprietary.

Stress-Blended Eddy Simulation

SBES is a fairly simple concept where existing RANS and LES models are 'blended' by a shielding (or blending) function. In the current approach, this is performed on the stress-level:

$$\tau_{ij} = \tau_{ij}^{RANS} f_s + \tau_{ij}^{LES} \left(1 - f_s\right) \tag{1}$$

In case both models are eddy-viscosity models (as is typically the case) the formulation simplifies:

$$\mu_t = \mu_t^{RANS} f_s + \mu_t^{LES} \left(1 - f_s\right) \tag{2}$$

In other words, SBES is not a new hybrid RANS-LES model, but a way to blend existing models to achieve optimal performance.

While the formulation is seemingly simple, its complexity is concentrated in the shielding function f_s, which has to satisfy the following requirements.

1. Provide high degree (asymptotic) shielding of RANS boundary layers under mesh refinement.
2. Switch reliably and swiftly from RANS to LES in SSLs.
3. Allow operation in WMLES mode.
4. Allow combination of all RANS and all (algebraic) LES models.
5. Remain robust even on non-perfect industrial meshes.

Previous authors have formulated model based on switching the eddy-viscosity [e.g. 4]. However, the resulting models have typically not been able to satisfy the above requirements. Especially requirement 1. is very hard to achieve, particularly in combination with point 4.

Shielding of RANS Boundary Layers

'Shielding' means that RANS boundary layers are protected against the LES (grid dependent) formulation to avoid compromising that portion of the solution. GIS is a very severe problem in general industrial flow simulations, as grid quality and resolution cannot be controlled to the level required by the design of DES/DDES.

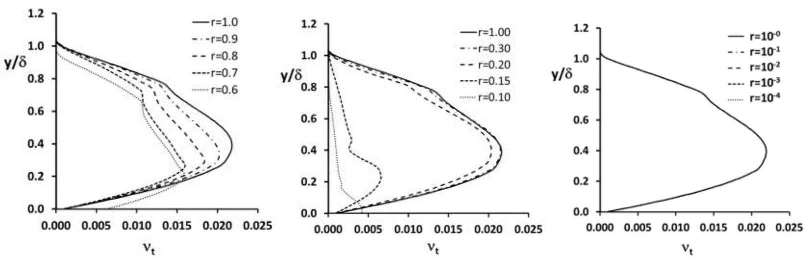

Figure 1: Eddy-viscosity profiles for DES(left) and DDES(middle) and SBES (right)under grid-refinement. (Note that range for SBES goes from $r=1\text{-}10^{-4}$).

Figure 1 shows eddy-viscosity profiles of DES and DDES and SBES under grid refinement. The parameter *r* is the ratio of the maximum edge length of the grid (as used in DES) relative to the boundary layer thickness. It can be seen that DES starts to deteriorate relative to the solid line (SST) once *r<1*. DDES provides improved shielding, but then also break down for *r~0.2*. It is interesting to note that while DDES is superior, it does break down much more rapidly due to the interaction of the impaired turbulence with the shielding function of that model (it should also be noted that IDDES provides only limited shielding – similar to DES). SBES provides perfect shielding even down to values of $r \sim 10^{-4}$ (note that the values for the grid spacing have been specified within the turbulence model by hand independent from the underlying mesh to avoid excessive CPU requirements). The ability of SBES to shield the RANS boundary layers far beyond what DES/DDES can achieve is an essential improvement in hybrid RANS-LES reliability. In addition, the strong shielding is a pre-requisite for blending the models at the stress level. Without such strong shielding, SBES could not maintain the RANS mode for boundary layers on almost any realistic mesh.

Rapid RANS-LES Transition

The ability to shift from RANS to LES in a SSL is tested with the help of a test case where a flat plate boundary layer goes past a 90° corner into a free mixing layer (**Figure 2)**. The single-stream mixing layer flow was experimentally investigated in [5]. The experimental section consists of a flat plate which suddenly terminates with a step (Figure 36), which induces the formation of the mixing layer from the separation point. The experiment is carried out at a Reynolds number of $Re_\theta=4650$ based on the momentum thickness θ of the incoming boundary layer and on the free-stream velocity U_0.

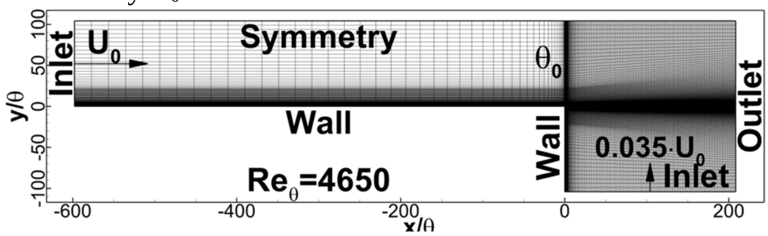

Figure 2: The domain and grid for the single stream mixing layer flow

Figure 3 shows iso-surfaces of the Q-criterion to visualize resolved turbulence structures. It can clearly be seen that SBES provides rapid transition between the RANS and the LES solution while DDES prevents the formation of 3D structures due to overly high eddy-viscosity levels. **Figure 4** shows the corresponding velocity and streamwise velocity fluctuation RMS value, again demonstrating the superior performance of SBES. (The SDES curve will be explained in the final paper).

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Summary

The concept behind the SBES model formulation has been explained. Specific characteristics of the model, like its asymptotic shieling properties and rapid RANS-LES transition have been demonstrated. The fully paper will also contain examples demonstrating the WMLES capability of the formulation.

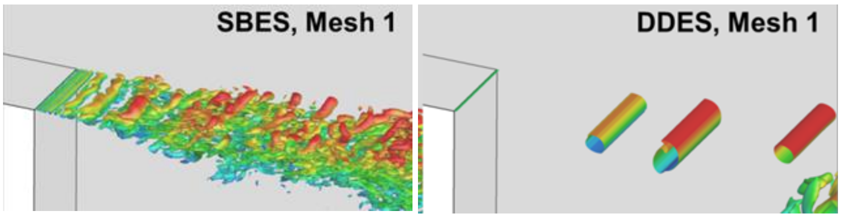

Figure 3: Iso-surfaces of the Q-criterion coloured with the velocity magnitude. Left SBES, right DDES

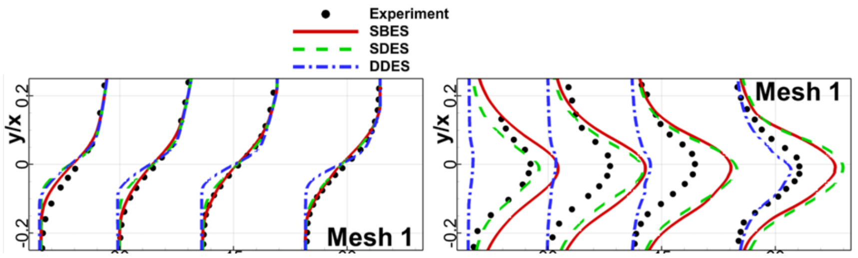

Figure 4: Profiles of the mean (left) and u'-RMS velocity (right) at different sections (x/θ=19.3, 29.6, 40.6, and 54.2) for mixing layer test case.

References

[1] Spalart, P. R. "Detached Eddy Simulation," Annu. Rev. Fluid Mech., vol. 41, pp. 181–202, 2009.

[2] Shur, M.L., Spalart, P.R., Strelets, M.K. and Travin, A.K., (2008), "A hybrid RANS-LES Approach with Delayed-DES and Wall-modeled LES Capabilities", International Journal of Heat and Fluid Flow 29, pp. 1638-1649.

[3] Spalart, P., Deck, S., Shur, M., Squires, K., Strelets, M., Travin, A. (2006), "A New Version of Detached Eddy Simulation, Resistant to Ambiguous Grid Densities", Journal of Theoretical and Computational Fluid Dynamics 20, pp. 181–195.

[4] Batten, P., Goldberg, U., Chakravarthy, S., 2002. LNS – An Approach towards Embedded LES. AIAA Paper 2002-0427.

[5] S. C. Morris and J. F. Foss, "Turbulent boundary layer to single-stream shear layer: the transition region", Journal of Fluid Mechanics Fluid Mech., vol. 494, pp. 187–221, 2003.