Investigation of the passage between LES and RANS subdomains in the framework of zonal RANS-LES approaches

M S Gritskevich¹, A V Garbaruk¹, F R Menter²

¹Peter the Great St. Petersburg Polytechnic University, 195251, St. Petersburg, Russia
²Software Development Department, ANSYS Germany GmbH, 83714, Otterfing, Germany

E-mail: gritckevich@gmail.com

Abstract. A detailed investigation of the passage between LES and RANS subdomains for zonal RANS-LES simulations of wall-bounded flows is performed with the main focus on the turbulent quantities reconstruction at LES-RANS interfaces. It is shown, that most accurate results are obtained if the turbulent quantities are specified from a precursor RANS simulation, while employing the actual solution from the LES subdomain is slightly less precise.

1. Introduction

Zonal RANS-LES approaches are now routinely applied to industrial flow simulations in order to balance computational and solution accuracy requirements. Within such approaches LES (Large Eddy Simulation) is used only in areas where RANS (Reynolds Averaged Navier-Stokes) models are not suitable, while RANS is used elsewhere. The main issue of such approaches is to provide a consistent blending when the mean flow crosses the interfaces between LES and RANS subdomains [1–3]. Depending on the flow direction, two types of interfaces can be distinguished, namely the RANS-LES interface (the flow from RANS to LES), and the LES-RANS interface (the flow from LES to RANS).

From the physical point of view, specification of the conditions at RANS-LES interfaces is the most difficult case, since the information required for the LES modeling is not readily available within the RANS solution. It should be mentioned that a number of elaborated methods for generating of the resolved turbulence from time-averaged RANS profiles are available in the literature [3–5], the best of which are highly accurate and compatible with general-purpose CFD codes.

At the same time, despite the apparent physical simplicity of the conditions at LES-RANS interfaces, their implementation into general purpose CFD codes is far from being straightforward. Particularly, the instantaneous LES velocity should be converted into the corresponding mean fields [3], which in principle, could be achieved with the use of an averaging procedure. However, for practical reasons, such methods could be only rarely applied for complex problems since the reconstruction of the turbulence quantities requires second order statistics, which is known to be very sensitive to the averaging sample and, therefore, requires a high level of computational time.

A possible alternative to the averaging is proposed in [6], where it is suggested to combine an algebraic sub-grid model in LES subdomains with a differential model in RANS subdomains. Within such an approach, the differential equations for the turbulent quantities are solved in the entire domain and, therefore, could be used at LES-RANS interfaces, while the resolved structures are suppressed due to the high eddy viscosity and dissipative upwind scheme in RANS subdomains.

It should be mentioned that solving of the RANS equations in LES subdomains on the basis of the resolved flow field yields excessive levels of the ‘RANS’ turbulent kinetic energy and eddy viscosity due to the higher velocity gradients of the LES flow field. This problem could be potentially avoided by utilizing the turbulent quantities at the LES-RANS interface from a precursor RANS simulation, however, some additional problems with such methods are anticipated if the precursor and the actual solutions are substantially different. In addition, another issue, which is known as turbulence kinetic energy “double accounting” [3], originates from the presence of both modeled and resolved turbulence...
at the LES-RANS interface resulting in a strong overestimation of the total kinetic energy and total shear stresses. This problem could, in principle, be reduced if the underlying RANS transport equations have a mechanism for adaptation of the modeled turbulence to the resolved scales (such models are sometimes termed as 2nd generation RANS models [1–3]), which decreases the modeled turbulent kinetic energy and results in more consistent conditions at LES-RANS interfaces.

Thus, the objective of the paper is to investigate different methods for the computation of turbulent quantities at the LES-RANS interface. The tests are carried out for fully developed channel flow [7] in the framework of the general purpose code ANSYS Fluent [8].

2. Test case description
Simulations of the channel [7] are conducted at Reynolds numbers of $Re_{\tau}=u_{\tau}h/\nu=395$ and $Re_{\tau}=18000$ ($u_{\tau}$ is the friction velocity, $h=0.5\cdot H$ is the channel half-height, and $v$ is the kinematic viscosity).

The computational domain for this flow (Figure 1) is decomposed into three subdomains referred to as AUX-LES, LES, and RANS with the dimensions of $4H\times H\times1.5H$, $2H\times H\times1.5H$, and $16H\times H\times1.5H$ respectively. The AUX-LES subdomain is used for the LES inflow turbulent content generation, thus eliminating the additional uncertainties due to synthetic turbulence generators.

![Figure 1. Computational setup for the developed channel flow](image.png)

The computational grid, consists of about $2\cdot10^6$ hexahedral cells, has the grid-steps of $\Delta x/H=1/10$ and $\Delta z/H=1/20$ in the streamwise and spanwise directions, while in the wall-normal direction a dense clustering is employed to satisfy $\Delta y^+<1$ for both Reynolds numbers.

The applied boundary conditions are shown in Figure 1. For all the considered subdomains, a $y^+$-insensitive wall treatment [9] is utilized at the top and bottom walls and the periodicity condition is specified in the spanwise direction. In the AUX-LES subdomain the periodicity condition is also specified in the streamwise direction and the flow is driven with a constant pressure gradient of $dp/dx=-2\cdot \rho\cdot u_{\tau}^2/H$ ($p$ is the pressure and $\rho$ is the density), which is taken into account in the governing equations via the source term in the momentum equations. At the LES inlet, the velocity and turbulence quantities are specified from the profiles extracted at each time step from the periodic boundary of AUX-LES. At the LES-RANS interface the turbulent quantities are either specified from the actual LES solution (one-stage or 1S approach) or from the precursor RANS simulation (two-stage or 2S approach). Finally, the constant pressure is specified at the RANS outlet.

It is worth mentioning that the convective fluxes for the momentum equations are computed with the use of the second order central differencing scheme in the AUX-LES and LES subdomains, while in the RANS subdomain the second order upwind scheme is employed.

3. Assessment of two-stage approaches
For the 2S approach, the flow is firstly computed entirely with the underlying RANS model. In the second stage, this RANS solution for $k$ and $\omega$ is frozen in the LES subdomain and kept in the background while the LES model is active. At the LES-RANS interface, the frozen solution from the two-equation model is re-activated, while resolved turbulence structures from the LES domain are allowed to pass into the RANS zone. It is then observed how quickly these structures are damped and how realistic the time averaged solution is compared to the known channel flow solution. Two underlining RANS models are considered for assessment of the two-stage approach [6], namely the
Shear Stress Transport model (2S-SST) [9] and the baseline version of the SST model (2S-BSL) [10], while in the AUX-LES and LES subdomains the eddy viscosity is calculated from the algebraic version of the Improved Delayed Detached Eddy Simulation (IDDES) [11].

As seen from the instantaneous vorticity iso-lines (Figure 2 and Figure 3) the resolved turbulent structures are observed downstream of the LES-RANS interface \((x/H=0)\) for both models, as expected. Particularly, for the near-wall location, large spanwise-elongated vortices can be distinguished up to \(x/H=6\), while at the channel center, the structures are more isotropic and decay slightly more rapidly regardless of the considered Reynolds number (the results for \(Re=18000\) are not shown).

![Figure 2. Vorticity iso-lines at the near wall section \((y/H=0.05)\) for \(Re=395\).](image)

![Figure 3. Vorticity iso-lines at the channel center \((y/H=0.5)\) for \(Re=395\).](image)

The skin friction coefficient distributions (Figure 4) show a noticeable discrepancy near the LES-RANS interface for 2S-BSL, while for 2S-SST only a small deviation is observed near the LES-RANS interface, while further downstream almost perfect agreement is achieved. It should be mentioned that the difference between 2S-SST and 2S-BSL is mainly attributed to the SST limiter [9] of the former, which decreases the eddy viscosity due to the noticeably larger velocity gradients of the LES solution resulting in a slower decay of the resolved turbulence in the RANS subdomain.

For the mean velocity (Figure 5), 2S-SST yields almost identical solutions to those of the reference RANS solution independently of the Reynolds number, while 2S-BSL profile has a slightly smaller slope at the logarithmic part due to the higher value of the skin friction coefficient.

![Figure 4. Distributions of the skin friction coefficient along the wall](image)

![Figure 5. Profiles of the mean velocity at different Re numbers at \(x/H=6\)](image)
Finally, the profiles of the total kinetic energy (sum of resolved and modelled) in Figure 6 show that 2S-SST and 2S-BSL provide almost identical solutions at the LES-RANS interface \((x/H=0)\), which are noticeably higher than the reference RANS due to the “double accounting” effect. Further downstream the resolved turbulence is suppressed by the RANS model and the total kinetic energy is recovering back to the reference solution.

Figure 6. Profiles of the total kinetic energy at different sections

4. Comparison of one-stage and two-stage approaches
For the 1S approach, the two-equation RANS turbulence model is run passively in the background of the LES simulation domain based on the unsteady LES flow field and the solution of the RANS model is then re-activated downstream of the RAN-LES interface. As it has been shown in the previous subsection, 2S-SST provides slightly better results than 2S-BSL for the skin friction and therefore, this model is used as the reference solution for the 1S approaches. For that purpose two turbulence models are considered namely the SST model (1S-SST) [9] and the SST based Scale-Adaptive Simulation (1S-SAS) [12]. It should be mentioned, that 1S-SAS, which is a 2nd generation RANS model, has the mechanism for the specific dissipation rate amplification in the presence of the resolved turbulent structures and, therefore, it could be anticipated that the resolved turbulence of 1S-SAS would be observed for a relatively large distance downstream of the LES-RANS interface. Indeed, as seen from the vorticity iso-lines (Figure 7 and Figure 8) 1S-SAS sustains the turbulent structures in the entire RANS subdomain. In contrast, 1S-SST provides almost immediate decay of the resolved turbulence downstream of the LES-RANS interface, which is even more rapid than those of 2S-SST.

Figure 7. Vorticity iso-lines for at the near wall section \((y/H=0.05)\) for \(Re_{\tau}=395\).

Figure 8. Vorticity iso-lines at the channel center \((y/H=0.5)\) for \(Re_{\tau}=395\).

However, as seen from the skin friction coefficient (Figure 9), both 1S models are less accurate than 2S-SST for both considered Reynolds numbers. Particularly, 1S-SST shows a substantial deviation near the LES-RANS interface, which is relatively slowly decaying downstream, while the skin friction of 1S-SAS is lower than the reference solution in the entire RANS subdomain. Consistently, 1S-SST yields slightly lower values of the mean velocity at the channel center (Figure 10), while 1S-SAS shows the opposite trend. Particularly, such behavior of 1S-SAS for the mean velocity profile is similar to the logarithmic-layer mismatch [11].
As seen from the modeled kinetic energy (Figure 11) both 1S-SST and 1S-SAS are noticeably different from the reference RANS solution at the LES-RANS interface. Particularly, 1S-SST noticeably overestimates the modeled kinetic energy near the LES-RANS interface due to the excessive turbulence generation in the LES subdomain and the “double accounting” effect when the flow re-enters the RANS subdomain, while 1S-SAS yields lower modeled kinetic energy due to its inherent sensitivity to the resolved turbulent structures. Finally, the total kinetic energy (Figure 12) for both 1S-SAS and 1S-SST is substantially higher at the LES-RANS interface \((x/H=0)\) than those of the reference RANS solution. Further downstream, 1S-SAS yields similar to 2S-SST profiles, while 1S-SST still noticeably overestimates the total kinetic energy at the channel center.

5. Summary
Several approaches for modeling of the passage between LES and RANS subdomains have been investigated with the main focus on recovering proper turbulence quantities.

It has been shown that the considered two-stage approaches (2S-SST and 2S-BSL) yield more accurate results than the one-stage approach (1S-SST and 1S-SAS), however, the mean velocity and the skin friction coefficient of the latter are still in a reasonable agreement with the reference RANS solutions.
At the same time, the total kinetic energy of the two-stage approaches is strongly overestimated due to the “double accounting” effect at the LES-RANS interface, which is more pronounced for 2S-BSL than for 2S-SST due to the SST correction [9] of the latter. Further downstream, both models provide a relatively quick recovering of the total kinetic energy. Nevertheless, it is worth mentioning that the two-stage approaches are inappropriate when the RANS and LES subdomains are strongly coupled or if the flow has an inherent unsteadiness (e.g. due to unsteady body motions).

With regards to one-stage approaches, due to an excessive turbulence generation in the LES subdomain and the “double accounting” effect, 1S-SST noticeably overestimates the total kinetic energy with a relatively slow recovery downstream. At the same time, 1S-SAS reasonably agrees with the reference RANS solution due to its inherent mechanism for resolved turbulence detection ensuring a physically consistent solution in RANS subdomains. On the other hand, 1S-SAS requires a relatively long distance in the RANS subdomain to completely suppress the resolved turbulence.

Acknowledgement
The authors from St. Petersburg are partially supported by Russian Foundation for Basic Research (grant No. 14-08-31121) and Russian Science Foundation (grant No. 14-11-00060). The computations are conducted with the support of Saint-Petersburg Branch of the Joint Supercomputer Center of the Russian academy of sciences.

References
[1] Sagaut P., Deck S. and Terracol M. 2006 Multiscale and Multiresolution Approaches in Turbulence
[2] Menter F. R., Schütze J. and Gritskievich M. S 2012 Global vs. Zonal Approaches in Hybrid RANS-LES Turbulence Modelling Progress in Hybrid RANS-LES Modelling, Notes on Numerical Fluid Mechanics and Multidisciplinary Design Volume 117 pp 15–28
[3] Frohlich J. and Von Terzi D. 2008 Hybrid LES/RANS Methods for the Simulation of Turbulent Flows Progress in Aerospace Sciences 44 349–77
[4] Nolin G., Mary I., Ta-Phuoc L., Hinterberger C. and J. F 2006 Coupling from LES to RANS using eddy viscosity models Direct and Large-Eddy Simulation VI vol 6 pp 679–86
[5] von Terzi D, Mary I and Frohlich J 2009 Segregated LES/RANS Coupling Conditions for the Simulation of Complex Turbulent Flows Numerical Simulation of Turbulent Flows and Noise Generation Volume 104 vol 104, ed C Brun, D Juvê, M Manhart and C-D Munz pp 231–52
[6] Cokljat D, Caridi D, Link G, Lechner R and Menter F 2009 Embedded LES Methodology for General-Purpose CFD Solvers Proceedings of 6th International Symposium on Turbulence and Shear Flow Phenomena pp 1191–6
[7] Moin P and Kim J 1982 Numerical investigation of turbulent channel flow Journal of Fluid Mechanics 118 341–77
[8] Mathur S R and Murthy J Y 1997 A pressure-based method for unstructured meshes Numerical Heat Transfer 32 195–215
[9] Menter F R, Kuntz M and Langtry R 2003 Ten Years of Experience with the SST Turbulence Model Proceedings of 4th International Symposium on Turbulence, Heat and Mass Transfer pp 625–32
[10] Menter F R 1993 Zonal two equation k-w turbulence models for aerodynamic flows AIAA Paper 1993-2906
[11] 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 1638–49
[12] Menter F R and Egorov Y 2010 The Scale-Adaptive Simulation Method for Unsteady Turbulent Flow Predictions. Part 1: Theory and Model Description Flow Turbulence and Combustion 85 113–38