Approximate near-wall treatments based on zonal RANS-LES hybrid methods for LES at high Reynolds numbers

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Large Eddy Simulation is now almost routinely used in Fluid Mechanics research to investigate fundamental aspects of turbulence mechanics, to help validate statistical closures and to obtain predictions for flows in which unsteady events associated with turbulence are of major interest or influence. Although LES continues to be an expensive approach at practically relevant Reynolds numbers, despite rapid advances in computer power, the expense is tolerable when the flow being simulated is remote from walls. However, flows which are substantially affected by near-wall shear and turbulence, pose serious resource challenges as a result of the need to increase the near-wall grid resolution in line with $N = O(Re^2)$, to restrict the distance between the wall and the nodes closest to the wall to around $y^+ = 2$ and to maintain a cell-aspect ratio of order $\Delta y^+ / \Delta s^+ = O(2, 20)$, where $s$ is any direction parallel to the wall. Thus, at high Reynolds numbers, the utility of LES in a practical context depends greatly on the availability of acceptably accurate near-wall approximations that allow the resolution requirements to be reduced to economically tenable levels.

Over the past few years, a whole range of approaches to this problem have been proposed. These include log-law-based wall-functions, various zonal and seamless RANS-LES hybrid schemes, the DES method, and the two-layer approach. So far, no one particular method has been demonstrated to be definitely superior to others, and all involve restrictions and limitations which adversely affect the resulting solution in some circumstances. Even in a simple fully-developed channel flow at high Reynolds number, no method is able to give a solution that is without defect in the vicinity of the edge of the near-wall layer within which the approximate model is applied.

In earlier work by Temmerman et al. (2004), a RANS-LES hybrid method has been investigated in which a conventional low-Re model is applied within a near-wall layer the thickness of which can be chosen freely, Fig. 1(a). Coupling to the LES domain is effected via compatibility constraints, including a dynamic process which adjusts the turbulent viscosity at the RANS side of the interface by reference to the Subgrid-scale viscosity in the LES layer.

![Figure 1: schematics of (a) the hybrid LES/RANS scheme; (b) and the two-layer model.](image-url)
In parallel, a second two-layer approach, of the general type proposed by (Balaras and Benocci, 1994; Wang and Moin, 2002), has been pursued and is reported, Fig. 1(b). In this approach, the near-wall layer is numerically separated from the LES domain. Simplified (parabolized) versions of the momentum and turbulence-model equations are solved in the layer, with boundary conditions for velocity and pressure gradient taken from the outer LES domain at the interface. The solution is then used to extract the wall-shear stress or a velocity at a particular location within the layer, which is then used as a boundary condition for the numerically separate LES domain. Here these two methodologies have been applied to a separated flow from the rear of an aerofoil at high Reynolds number ($Re = 2.15 \times 10^6$). Fig. 2 relates to a separated flow that evolves along an asymmetric trailing edge of a model hydrofoil. The Reynolds number, based on free stream velocity $U_\infty$ and the hydrofoil chord, is $2.15 \times 10^6$. The corresponding Reynolds number, based on hydrofoil thickness, is $101,000$. Simulations were performed over the rear-most 38% of the hydrofoil chord. The flow had previously been investigated experimentally by Blake and numerically by Wang and Moin (2002). The computational domain is $0.5h \times 41h \times 16.5h$, where $H$ denotes the hydrofoil thickness. Four sets of profiles are presented for the velocity magnitude and the streamwise turbulent intensity, one of which arises from the reference solution with a mesh containing $1536 \times 96 \times 48$ nodes, Wang and Moin (2002). The other three sets of profiles were obtained, respectively, with a log–law wall function, a 1–d solution of the sublayer RANS equations (with transport and pressure gradient omitted, denoted by $F_i = 0$. in Fig 2) and the third with pressure gradient included and imposed on the sublayer by the outer LES field (denoted by $F_i = \frac{\partial p}{\partial x_i}$). The main observation is that the wall-function and one dimensional implementations give similar results, while the inclusion of the pressure gradient improved the representation of the flow. The former observation is expected, for the 1–d implementation returns, essentially, the log–law solution. Fig. 3 relates to the hybrid RANS–LES scheme, in this case the grid has been stretched to the wall in the normal direction, the other two grid distributions remaining unchanged. The mean velocity profile show fairly close agreement between the full–les and the hybrid RANS–LES scheme in the first two sections, but the separation point and the recirculation bubble are not captured by the low Reynolds $k – l$ model. The comparison reported in Fig. 3 for the rms streamwise velocity confirm this observation, possible reasons for this disagreement are the presence of strong three dimensional and non equilibrium effects in the separation region. Further computations are in progress and evaluation of $k – \epsilon$ model in the RANS layer will be reported.

![Figure 2](image_url)  

**Figure 2**: Magnitude of mean velocity (left), rms streamwise velocity (right) at $x/H = -3.125, -2.125, -1.625, -1.125, -0.625$; present results wall model $F_i = \frac{\partial p}{\partial x_i}$, ---- full LES, --- wall function, -- -- wall model $F_i = 0$.  

Figure 3: Magnitude of mean velocity (left), rms streamwise velocity (right) at $x/H = -3.125, -2.125, -1.625, -1.125, -0.625$; —— hybrid RANS–LES with one equation and dynamic Smagorinsky LES model.

References

