Wall-modelling strategies in large eddy simulation of separated high-Reynolds-number flows

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The need to develop wall-modelling strateguiess arises from the fact that the detailed resolution of near-wall turbulence becomes untenably expensive as the Reynolds number of the flow increases to level approaching that pertaining to real-world applications. The problem is conveyed by Fig. 1, taken from Piomelli & Balaras (2002). The figure shows that, when Re_L (say, that based on the boundary layer thickness) exceeds roughly 10^5, the resource requirements are entirely dominated by the need to resolve the near-wall region (the inner layer), with the number of nodes rising roughly as $N \propto Re_L^{2.5}$. Simulations for practical configurations would not, in most circumstances, be undertaken today with meshes exceeding 10-50 million nodes, corresponding to $Re_L \approx 5\times10^5$, yet this is still a very modest Reynolds number in practice. The limitations conveyed by Fig. 1 are of particularly serious concern in external aerodynamic flows, which are dominated by high-speed boundary layers that are often close to or beyond separation, due to geometric features or adverse pressure gradient arising from high incidence. In such circumstances, the correct resolution of the near-wall structure of the flow can have a decisive influence on the overall predictive quality of a computational prediction.

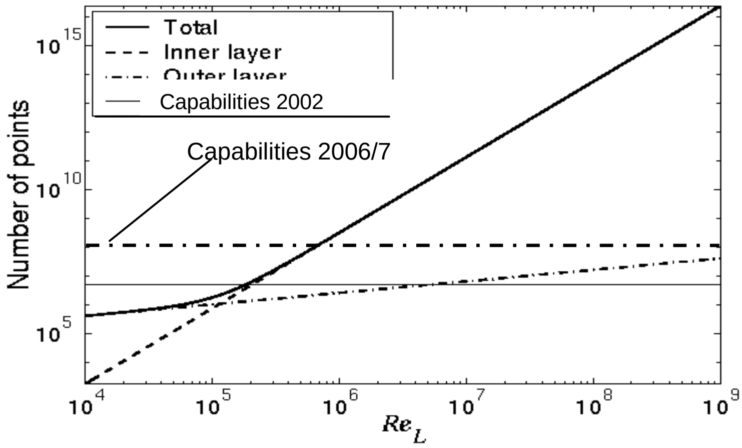

Fig. 1: Resolution requirements of LES as a function of Reynolds number

The general approach taken in recent years towards addressing the problem of near-wall resolution has been to combine RANS modelling near the wall with LES in the outer flow. The key premise underpinning this strategy is that it should allow near-wall numerical cells to be used that have far higher aspect ratios than those required by LES, typically 500-1000, relative to 50 in wall-resolving LES. Substantial savings could thus be made by using much coarser streamwise and spanwise meshes than are dictated by the LES constraints.

Efforts at Imperial College have focused on two particular methods, one being a hybrid LES-RANS scheme and the other being a two-layer zonal schemes. Both are documented in detail by Temmerman et al (2004) and Tessicini et al (2006). The difference between them is explained by reference to Fig. 2, which conveys the manner by which the LES and RANS regions communicate numerically.

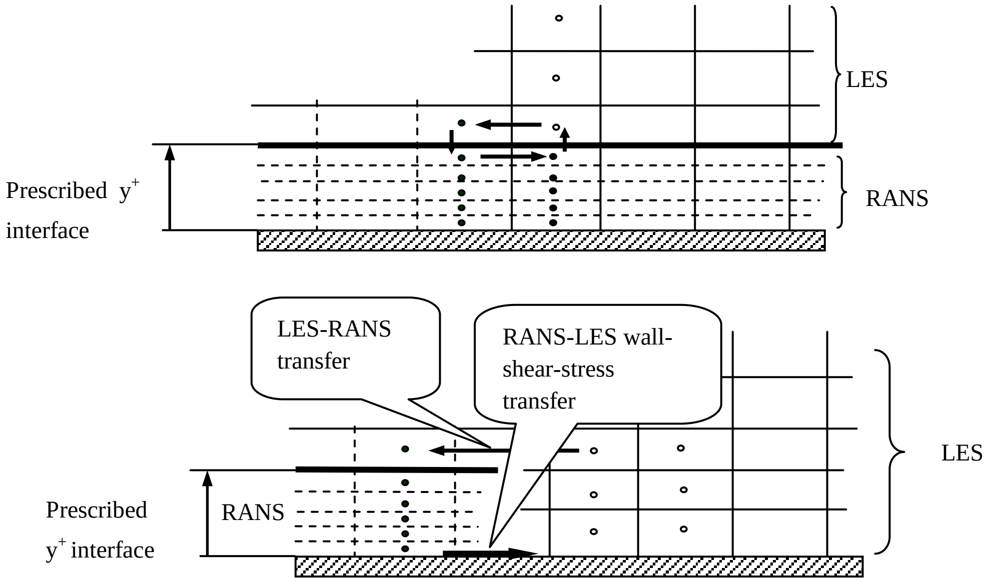

Fig. 2: Schematics of hybrid LES-RANS scheme (upper) and two-layer zonal scheme (lower)

The hybrid method uses a single computational domain. Within a predefined layer near the wall, that can be prescribed in terms of y^+, RANS equations are solved using one-equation or two-equation eddy-viscosity models that are dynamically adjusted so to comply with continuity of eddy viscosity across the interface, $\nu^{RANS} = \nu^{LES}$, beyond which a LES subgrid-scale model is used. To achieve this compatibility, the RANS model coefficients at the interface is determined by comparison of the RANS viscosity, containing the RANS-determined turbulence energy and dissipation rate at the interface, to the LES viscosity at the interface. The variation of the coefficients from the interface to the wall is then prescribed analytically, based on observations derived from a-priori wall-resolved LES performed in channel flows.

The zonal method uses two overlapping grids across the near-wall layer. The LES grid extends to the wall, but is relatively coarse, maintaining cell-aspect-ratio constraints appropriate to LES. Within the near-wall layer, a separate grid is inserted, which is refined towards the wall, typically to a wall-nearest node located at y^+=O(1). Within that layer, parabolized RANS equations are solved for the wall-parallel-velocity components, using a simple algebraic turbulence model - for example, a mixing-length model.

Importantly, the wall-parallel pressure gradient in the near-wall layer is imposed on the layer from the LES solution, evaluated from the LES nodes closest to the interface. Thus, the pressure field need not be determined in that layer. In the simplest implementation, advection in the sublayer is also ignored, rendering the near-wall model one-dimensional and very cheap to solve. However, convection has been fully included and its the role has been investigated (Leschziner et al (2007). The reverse RANS-to-LES coupling involved only the extraction of the wall-shear stress from the parabolized equations and feeding it into the LES solution as a wall boundary condition.

The performance of both methods for channel and several separated flows is discussed in Temmerman et al (2004) and Tessicini et al (2006, 2007). In particular, channel-flow solutions for *Re*=42000 have been examined in detail. The main conclusion emerging from these investigations is that the use of either wall model is extremely advantageous, although a weak inflection in the log-law region returned by the hybrid scheme indicates that the level of turbulence, and hence turbulent shear stress, is too low around the interface.

The main emphasis of the research was in investigating separated flows. The two main configurations investigated are shown in Figs. 3 and 4. A third configuration, a highly-swept wing at high incidence, is also one to which the present zonal; scheme has been applied, but this work is the subject of a separate summary in this webpage. Both cases discussed here required precursor boundary-layer simulations to be undertaken in order to enable the full time-dependent inflow conditions to be prescribed. These simulation are themselves resource-intensive, especially in the configurations of Fig. 4.

The first case is a flow, at Re=2.16x10^6 based on the chord, separates from the upper side of a zero-camber aerofoil. In this simulation, the near-wall layer was placed at y^+=40 (evaluated just upstream of the curved section). A wall-resolved computation had been performed by Wang & Moin (2000) with 7 million nodes, while the present solution was obtained with a mesh of 1.5 million nodes. Fig. 5 shows distributions of the time-mean skin-friction coefficient, predicted with and without the pressure gradient included in the parabolized equations in the RANS layer. The skin friction is a sensitive indicator of the realism of the near-wall solution, and the results are certainly encouragingly close to the benchmark solution. Comparisons of velocity and turbulence-intensity profiles, reported by Tessicini et al (2006), also show good agreement, especially for the zonal scheme.

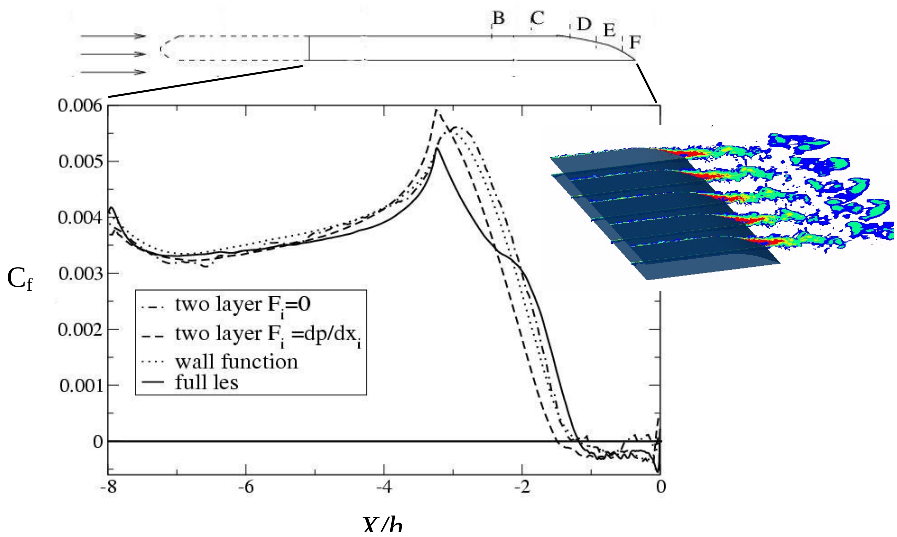

Fig. 3: Skin-friction coefficient over the rear suction side of a zero-camber aerofoil computed with a two-layer zonal scheme, a wall-function approach and a wall-resolving LES

The second case is the flow in a duct around a 3d circular hill placed in the duct. This flow, at a Reynolds number of 130,000 (based on hill height and duct velocity), has been the subject of extensive experimental studies by Simpson et al (2002) and Byun & Sympson (2005). Results reported herein are taken from a broader exposition given in a recent paper by Tessicini et al (2007). The size of the computational domain is 16H x 3.205H x 11.67H, with H being the hill height. The hill crest is 4H downstream of the inlet plane. The inlet boundary layer, at -4H, was generated by a combination of a RANS and LES precursor calculations, the former matching the experimental mean-flow data and the latter providing the spectral content. Simulations were undertaken with meshes containing between 1.5 and 36.7 million nodes, the finest-grid simulation being fully wall-resolving. Coarser grids were used in conjunction with the zonal scheme, wherein the interface was placed within y^+=20-40 and 40-60, using 3.5 and 1.5 million nodes, respectively. The fully-resolved simulation is the most resource-intensive computations ever undertaken by the writer's group, requiring some 70000 CPU hours. Apart from providing a 'gold standard' against which to compare wall-approximating simulations, the finest-grid simulation allowed an in-depth analysis of the near-wall flow physics to be undertaken. Initial results for this particular simulation are reported in Li and Leschziner (2007), and an-depth analysis is to be reported shortly in a Garcia-Villalba et al (2007).

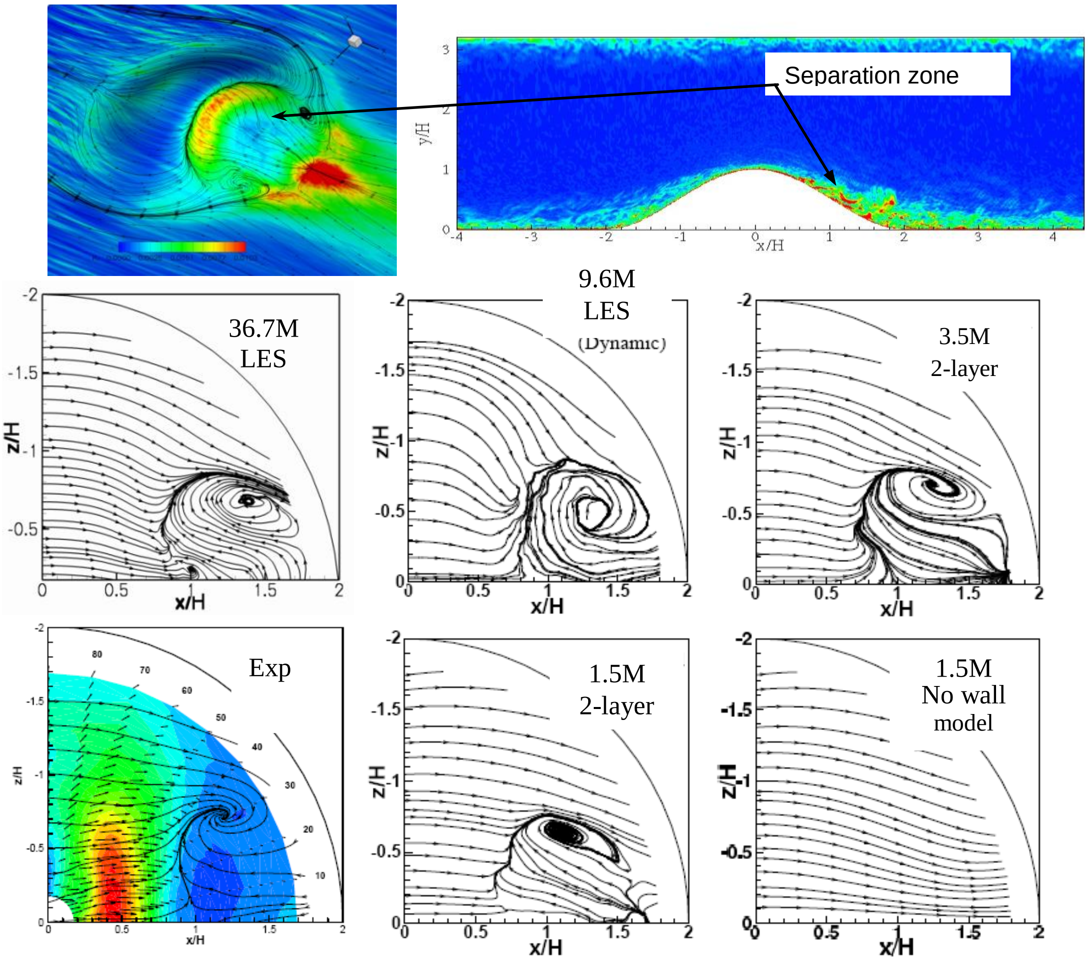

Fig. 4: Wall-limiting streaklines indicating the separated-flow topology over the rear part of the surface of a 3d hill in a duct (upper plots indicate the general features of the flow

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