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A Hybrid LES–RANS Technique Using an Explicit Algebraic Reynolds Stress Model

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ABSTRACT

Large–eddy simulations (LES) still suffer from extremely large resources required for the resolution of the near–wall region, especially for high–Re flows. That is the main motivation for setting up hybrid LES–RANS methods. Meanwhile a variety of different hybrid concepts were proposed mostly relying on linear eddy–viscosity models (LEVM). In the present study a hybrid approach based on an explicit algebraic Reynolds stress model (EARSM) designed by Wallin and Johansson [6] for pure RANS applications is suggested. The model is applied in the RANS mode with the aim of accounting for the Reynolds stress anisotropy emerging especially in the near–wall region. For the implementation into a CFD code the anisotropy–resolving closure can be formally expressed in terms of a non–linear eddy–viscosity model (NLEVM). The EARSM of Wallin and Johansson [6] was chosen because of its near–wall treatment ensuring realizability of the individual stresses. Furthermore, its extra computational effort is small still requiring solely the solution of one additional transport equation for the turbulent kinetic energy. In addition to this EARSM approach, a LEVM is used in order to verify and emphasize the advantages of the non–linear formulation. The EARSM provides an algebraic relation for the Reynolds stress tensor [6], which can be introduced in the momentum equation as $\overline{u_i' u_j'}_{mod} = k_{mod} \left(\frac{2}{3}\, \delta_{ij} - 2\, C_\mu^{eff}\, \overline{S}_{ij} + a_{ij}^{(ex)} \right)$. Here $a_{ij}^{(ex)}$ represents an extra anisotropy tensor which is computed explicitly at low computational costs based on the normalized mean strain and rotation tensors. Hence in this formulation the k–equation is still needed but the additional term takes the anisotropy of the stresses appropriately into account. Additionally, the enhanced representation of the Reynolds stresses can be introduced into the turbulent diffusion term in the k–equation. Thus, in addition to the classical gradient–diffusion model the diffusion model of Daly and Harlow [2] is implemented. A further consequence of applying an EARSM is on the production term in the k–equation, which can now be calculated on the basis of the more consistent Reynolds stress formulation including the anisotropy term. Hence, the production and diffusion terms and subsequently k_{mod} are improved.

In previous studies [1, 3] the linear eddy–viscosity one–equation model suggested by Rodi et al. [4] for the viscosity–affected near–wall RANS layer was combined with a one–equation SGS model of Schumann [5] in the outer LES region. The resulting unique model consists of a transport equation for the modeled turbulent kinetic energy k_{mod} in RANS and the subgrid–scale turbulent kinetic energy k_{sgs} in LES mode, respectively. For LES the length scale is naturally given by the filter size Δ, whereas

for RANS in the near–wall region it can be expressed by an analytical relation. Since the wall–normal velocity fluctuations $(\overline{v'^2})^{1/2}$ are better suited to characterize the near–wall turbulent motion than k_{mod} [4], they are used as velocity scale in the RANS model. Introducing an algebraic equation relating the wall–normal velocity fluctuations to k_{mod} [4] assures that the transport equation does not have to be modified. In the present formulation the predefinition of RANS and LES regions is avoided and a

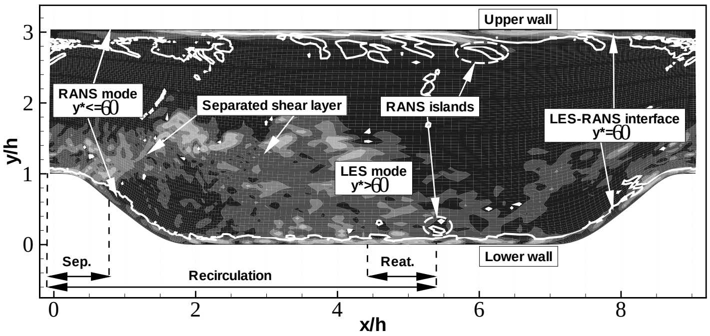

Figure 1: Periodic hill flow. Region definition, snapshot of the LES–RANS interfaces (white line) and contour of k_{mod} for the non–linear hybrid approach. Dark region: low k_{mod}. Bright region: high k_{mod}.

gradual transition between both methods is assured. A dynamic interface criterion is suggested which relies on the modeled turbulent kinetic energy and the wall distance and thus automatically accounts for the characteristic properties of the flow (see Fig. 1). Furthermore, an enhanced version guaranteeing a sharp interface is proposed. The interface behavior is thoroughly investigated and it is shown how the method reacts on dynamic variations of the flow field.

Both model variants, i.e. LEVM and EARSM, have been tested on the basis of the standard plane channel flow at $Re_\tau = 595$ and 2003 and even more detailed on the flow over a periodic arrangement of hills at $Re = 10,595$ using fine and coarse grids. Overall the flow field is well reproduced by the hybrid approach. Concerning the mean velocity and the Reynolds stresses, irrespective of the hybrid version these fields are overall recovered. However, the non–linear version shows better performance than the linear variant and is in good agreement with the LES reference. Besides, other favorable behaviors of the non–linear version are observed for the wall–shear stress τ_w and the Reynolds stresses. At the hill crest the linear approach strongly overpredicts the peak of τ_w. Contrarily, with the additional EARSM this discrepancy disappears. The superiority of the non–linear variant over the linear is also noticeable through the disappearance of discrepancies from the reference LES and unphysical comportments (e.g., $\overline{v'v'}$ in the vicinity of the wall) observed for the linear approach. Further results will be provided in the paper.

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