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An Implicitly Consistent Formulation of a Dual-Mesh Hybrid LES/RANS Method

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Abstract. A consistent dual-mesh hybrid LES/RANS framework for turbulence modeling has been proposed recently (H. Xiao, P. Jenny, A consistent dual-mesh framework for hybrid LES/RANS modeling, J. Comput. Phys. 231 (4) (2012)). To better enforce componentwise Reynolds stress consistency between the LES and the RANS simulations, in the present work the original hybrid framework is modified to better exploit the advantage of more advanced RANS turbulence models. In the new formulation, the turbulent stresses in the filtered equations in the under-resolved regions are directly corrected based on the Reynolds stresses provided by the RANS simulation. More precisely, the new strategy leads to implicit LES/RANS consistency, where the velocity consistency is achieved indirectly via imposing consistency on the Reynolds stresses. This is in contrast to the explicit consistency enforcement in the original formulation, where forcing terms are added to the filtered momentum equations to achieve directly the desired average velocity and velocity fluctuations. The new formulation keeps the averaging procedure for the filtered quantities and at the same time preserves the ability of the original formulation to conform with the physical differences between LES and RANS quantities. The modified formulation is presented, analyzed, and then evaluated for plane channel flow and flow over periodic hills. Improved predictions are obtained compared with the results obtained using the original formulation.

AMS subject classifications: 76F65

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1 Introduction

In the past two decades Large Eddy Simulation (LES) has been successfully used to study flows in a wide variety of applications. However, its high computational cost for wall-

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bounded flows at high Reynolds numbers still is a major hurdle for applications to practical flows in industry and nature [1]. This is due to the difficulty in resolving the small but important near-wall eddies in LES, since the computational cost of resolving such eddies scales as $Re^{1.8}$ according to Chapman [2] or $Re^{13/7}$ according to a more recent estimation by Choi and Moin [3], where Re is the Reynolds number. To overcome this difficulty, many hybrid LES/RANS (Reynolds Averaged Navier-Stokes) methods have been proposed, where the RANS equations are solved in the near-wall region and LES is conducted in the free-shear domain away from walls. In this strategy statistics of the small eddies near the wall is computed by a RANS model instead of being resolved in an LES.

Recently, Xiao and Jenny [4] developed a novel hybrid LES/RANS framework, where LES and RANS simulations are conducted simultaneously on the entire domain on separate meshes. Relaxation forces are applied on the respective equations to ensure consistency between the two solutions, hence the designation *consistent dual-mesh* hybrid LES/RANS framework. Within this framework, a hybrid LES/RANS solver for incompressible flows called HybridLRFoam has been developed based on the open-source CFD platform OpenFOAM [5]. Preliminary investigations were conducted of plane channel flow and of flow over periodic hills at different Reynolds numbers. The results show that the proposed method leads to satisfactory results on relatively coarse meshes, which is promising for industrial flow simulations [4, 6]. Xiao et al. [7] extended the original solver by utilizing a high-order, Cartesian-mesh-based in-house LES solver IMPACT [8,9] in lieu of the second-order OpenFOAM-based LES solver in HybridLRFoam. A volume-penalization method was used to impose wall boundary conditions for IMPACT. The two hybrid solvers differ only in the LES solver used and are based on the same coupling scheme. The obtained solver, named ImpactFoam, demonstrated the flexibility of the coupling scheme in accommodating different RANS and LES solvers.

In both HybridLRFoam [4, 6] and ImpactFoam [7] the relatively simple two-equation k–ε model of Launder and Sharma [10] was used, although the proposed framework is flexible enough to accommodate other RANS turbulence models. For the periodic hill test case, the solver led to excellent predictions in the attached regions for both mean velocity profiles and wall friction coefficients. However, in the separated region the prediction of the hybrid solver was not completely satisfactory. A likely reason therefore is the limitations of the relatively simple RANS model which was active in this region. It is well-known that k–ε models do not perform well in flows with recirculation and adverse pressure gradients. Billard [11] evaluated several eddy-viscosity models and Reynolds stress transport models for flow over periodic hills and other separating flows. Among the models he evaluated the Reynolds stress transport model with elliptic relaxation led to the best prediction of flow separations, and they emphasized that careful selection of the underlying RANS model in a hybrid LES/RANS approach is very important.

A Reynolds Stress Transport Model with Elliptic Relaxation (RSTM-ER) was proposed by Durbin [12] based on the LRR Reynolds stress transport model of Rodi et al. [13]. In this model, an elliptic operator takes into account the non-local effects of the wall on