DEVELOPMENT OF INTERPOLATED HYBRID RANS-LES SOLVERS FOR TURBULENT FLUID FLOWS

by

Ashutosh Kumar Jaiswal

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Department of Applied Mechanics

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Abstract

Flow solvers based on Large Eddy Simulation (LES) and Reynolds Averaged Navier Stokes (RANS) equations have emerged as important tools for simulating wall-bounded turbulent flows at high Reynolds number. Wall-resolved LES is, however, quite computationally expensive at high Reynolds number, whereas RANS models require calibration for different flow geometries. Hybrid RANS-LES simulations have emerged as an attractive alternative to stand-alone LES or RANS solvers, in which large-scale velocity fluctuations are accurately resolved in the free-stream region without requiring high wall-parallel grid resolution near the wall. Due to their relatively low computational cost compared to wall-resolved LES and higher accuracy compared to RANS solvers, hybrid RANS-LES solvers have become popular for simulation of engineering fluid flows in complex geometries. However, conventional hybrid RANS-LES solvers enforce an abrupt transition of the subgrid stress model between the near-wall and free-stream regions, which leads to the modeled stress depletion, in which neither the resolved nor modeled stress are able to contribute effectively within the transition zone. As a result, hybrid RANS-LES solvers underpredict the wall shear stress. In this thesis, interpolated hybrid RANS-LES models are presented, in which the flow domain is demarcated into three zones based on the distance from the wall: the “near-wall”, “free-stream”, and “hybrid” zones. The hybrid zone is sandwiched between the near-wall and free-stream zone, and its thickness is proportional to the local grid cell width. Large Eddy Simulation equations for the filtered velocity field along with Reynolds Averaged Navier Stokes equations for the RANS eddy viscosity are evolved on the same computational grid across the entire domain. A hybrid Reynolds stress is then obtained via interpolation of the resolved stress predicted by LES in the free-stream region and Reynolds stress predicted by RANS in the near-wall region. The interpolation is carried-out in the “hybrid” region via solution of an elliptic partial differential equation for the interpolants. The hybrid Reynolds stress is then used to correct the sub-grid stress in the mean LES momentum equation within the “hybrid” and “near-wall” zones. Modeled stress depletion and underprediction of the wall shear stress is successfully avoided with this strategy. Several versions of the interpolated hybrid RANS-LES technique have been presented in this thesis. The Interpolated RANS-LES (IRL) solver interpolates only the effective eddy viscosity, whereas the Interpolated Reynolds-stress RANS-LES (IRRL) solver interpolates all the components of the deviatoric part of Reynolds stress separately. Additionally, an Interpolated Wall-modeled LES (IWLES) solver is formulated, where the first off-wall grid cell thickness exceeds the viscous length scales, and the hybrid Reynolds stress is directly interpolated between the turbulent wall shear stress and the resolved stress in the free-stream region. The interpolation-based schemes have been implemented in the PimpleFOAM solver in OpenFOAM-v7. The solvers have been validated against Direct Numerical Simulation (DNS) data and LES data for canonical flow geometries such as, fully developed channel flow, flow over backward facing step and flow over periodic hills. Moreover, the results from IRL and IRRL solvers have been compared against results from Detached Eddy Simulations (DES). A careful sensitivity analysis has been carried out for IRL solver in which the effect of thickness of the hybrid region on the predicted flow statistics has been examined. Both IRL and IRRL solvers are able to yield better predictions compared to DES for wall shear stress within the attached turbulent boundary layers. IWLES is able to correctly capture the law of the wall in turbulent channel flow for a range of grid resolutions and Reynolds numbers. This thesis successfully demonstrates the utility of interpolation based techniques towards addressing the modeled stress depletion in conventional hybrid RANS-LES and wall-modeled LES (WMLES) approaches.