Reynolds-constrained Subgrid-scale Modelling for Large-eddy Simulation of Turbulent Wall Flows

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Abstract: In computational fluid dynamics (CFD) applications, the Reynolds Averaged Navier-Stokes (RANS) simulations suffer from the lack of robustness and universality of the turbulence models, especially for unsteady flows with massive separations. Meanwhile, the application of traditional large-eddy simulation (LES) method to wall-bounded flows of engineering interest is still far from feasible due to the intolerable grids requirement. Although the hybrid RANS-LES approaches (e.g., the detached-eddy simulation, abbreviated as DES) have achieved notable success, yet they may suffer from the log-layer mismatch (LLM) phenomenon, which may cast doubts on the effectiveness and fidelity of the hybrid approaches. In the present paper, a constrained large-eddy simulation (CLES) technique is introduced in order to open up a new way of modelling subgrid-scale (SGS) effects for LES of wall-bounded turbulent flows.

For CLES of wall-bounded flows, the low-pass filtered Navier-Stokes equations are solved in the entire domain with the SGS models constructed in different forms within the near-wall and far-wall regions. In the far-wall region, traditional SGS models (e.g., Smagorinsky-Lilly model) are employed, whereas in the near-wall region, the mean SGS models are constrained by prescribed Reynolds quantities.

The proposed CLES methods are tested and validated in simulations of several typical flows, including turbulent channel flows, flow past two tandem circular cylinders, flow over a compression ramp, etc. For attached flows, the CLES method can eliminate the nonphysical LLM phenomenon reported in hybrid RANS-LES methods, and can predict the mean velocity and temperature profiles, friction force and other statistical quantities more accurately than traditional LES and hybrid RANS-LES methods. For detached flows, CLES can calculate the skin friction force more precisely than traditional LES, and is comparable to DES in prediction of the aerodynamic statistics. Moreover, the CLES method proves to be much less sensitive to the grid resolution than traditional LES and DES methods, and makes pure LES of flows of engineering interest feasible on moderate grids.

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