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

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Introduction

In computational fluid dynamics (CFD) softwares, the Reynolds Averaged Navier-Stokes (RANS) simulation based on various turbulence models is the most widely employed method due to the low computational cost. However, most of the RANS models suffer from the lack of robustness and universality, especially for unsteady flows with massive separations. However, 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 [1]. 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 [1, 2]. 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.

Reynolds-constrained Subgrid-scale Modelling

For CLES of wall-bounded flows, the low-pass filtered Na-vier-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 mo-dels (e.g., Smagorinsky-Lilly model) are employed, whereas in the near-wall region, the mean SGS models are constrained by prescribed Reynolds quantities.

For incompressible case, in order to model the SGS stress based on the resolved velocity, one can compare the RANS and the LES equations and obtain a balance relation between the total calculated Reynolds stress and an external Reynolds stress. In the near-wall region, the SGS stress model is decomposed into a mean part and a fluctuating. The mean SGS stress is given by the balance relation, and the fluctuating part can be parameterized based on the Smagorinsky-type model. The model coefficient can be determined using the dynamic procedure suggested by Lilly [3] based on the Germano identity [4]. In the far-wall region, the traditional dynamic Smagorinsky model (DSM) is used as usual [3].

Session:

For compressible case, both the SGS stress tensor and the SGS heat flux need to be modelled based on the resolved density, velocity and temperature fields, respectively. Accordingly, the SGS stress and heat flux are split into a mean part and a fluctuating part. The mean SGS stress and heat flux are constrained by prescribed external Reynolds stress and heat flux, respectively, and the fluctuating SGS effects can be parameterized in terms of, e.g., the traditional compressible Smagorinsky formulations [5]. In the far-wall region, traditional Smagorinsky models for the SGS stress and heat flux can be used as in [5].

Numerical Validation

The proposed CLES methods [6, 7] 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. The simulation results are well compared with the available numerical and experimental data, as well as those from numerical simulations using other approaches. For attached flows, the CLES method can eliminate the non-physical 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 make pure LES of flows of engineering interest feasible on moderate grids.

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