



A dynamic hybrid RANS/LES approach based on the local flow structure



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ABSTRACT

By extracting the structural function from Vreman eddy-viscosity subgrid-scale model, a new turbulent length scale, which could quantify the degree of the instability of the local flow, is proposed. A hybrid RANS/LES method that combines both this kind of length scale and wall distance is obtained. The new model is capable of automatically determining the “transition” from RANS region to LES region according to the local flow state, instead of just taking the grid spacing into consideration. To investigate the WMLES (Wall-modeled LES) capability of this model, it is applied to fully-developed plane channel flows with two coarse grids whose grid numbers in wall parallel directions are respectively 37×37 and 49×49 . Re_τ ranges from 590 to 12,500. Most of the turbulent structures are resolved and sufficient resolved stresses are provided even near the wall. The prediction of mean velocity profiles is adequately accurate, and the phenomenon of “log layer mismatch” is removed. Flows pass a circular cylinder at subcritical Reynolds number is selected as an additional test case to explore the new model's performance subjected to separated flows. The present model has the potential of obtaining encouraging results with economical computation cost.

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1. Introduction

Due to the major interest of accurately resolving turbulent integral scales, the cost is prohibitively expensive for the application of Large Eddy Simulation (LES) in wall-bounded turbulent flow at industrially relevant Reynolds numbers (Choi and Moin, 2012). However, at high Reynolds number, the employ of acceptably accurate Wall-Modeled LES (WMLES) allows the required grid resolution to be reduced to an economically tenable level.

Over the past decades, a whole range of WMLES models were proposed with coarse grid resolution (Piomelli, 2008). The first type of WMLES is the so-called equilibrium layer model, which assumes the existence of a logarithmic law that connects the velocity in outer layer with wall stress in an algebraic way. In this approach, a wall shear stress model or wall function which supplies instantaneous wall shear stress to LES is used as the approximate wall boundary condition instead of no-slip condition. Only the outer flow is resolved with a fairly coarse grid and the first grid point in the wall-normal direction is located far from the wall, especially at high Reynolds number. The wall stress model was pioneered by Schumann (1975). Piomelli et al. (1989) introduced

the shifted model, which is a modified version of Schumann's approach, to take into account the near-wall inclined eddies. Later, Nicoud et al. (2001) proposed a suboptimal control theory to generate boundary conditions for wall shear stress. This control theory was capable of minimizing the numerical and modeling errors. Recently, Lee et al. (2013) applied the mean wall shear stress as wall boundary condition rather than the instantaneous one in their wall stress model, and showed that it accurately predicts the mean velocity profile and the skin friction distribution in turbulent channel flow at high Reynolds numbers. This type of WMLES, however, receives some limitations in complex flows such as the massive separated flows in which the assumption of logarithmic law is not valid.

The two-layer model (TLM), another type of WMLES, originally introduced by Balaras et al. (1996), and tested by Cabot and Moin (2000), has mutual relations between the inner and outer layer. In this approach, LES equations are solved in the boundary layer with very coarse grid resolution near the wall, and the first off wall grid point is located at $y^+ \sim 50$, where y^+ is the non-dimensional distance in the wall-normal direction. Between this grid point and the solid wall, a refined mesh is embedded and simplified turbulent boundary-layer (TBL) equations are solved to supply the wall stress to the outer layer, while LES provides the instantaneous solution to the inner layer in turn. Wang and Moin (2002) obtained more accurate results using a dynamically

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adjusted mixing-length eddy viscosity in TBL equations. Kawai and Larsson (2010) proposed a mesh-resolution-dependent dynamic wall model and showed quite well predictions in the supersonic turbulent boundary layer.

Detached Eddy Simulation (DES) is one hybrid method that combines the solutions of the Reynolds-Averaged Navier-Stokes (RANS) equations in the entirely boundary-layers with the solutions of the LES equations in the separated regions. DES was first proposed by Spalart et al. (1997) to address the high Reynolds number, massively separated flows. However, Nikitin et al. (2000) used DES as a wall-modeled LES in calculations of the channel flow at a wide range of Reynolds numbers without introducing any complexity. That is to say, the DES model is applied as a plausible Subgrid-Scale (SGS) model in the LES of channel flow and it acts as both RANS and LES models for the near-wall layer and outer flow, respectively. In the “LES region”, the grid spacing parallel to the wall is set to be far smaller than the boundary-layer thickness. The grid in the wall-normal direction is refined and $y^+ \sim 1$ for the first grid point is maintained. The results showed that turbulence was sustained, and stable calculations were obtained even though the grids were not fine enough. However, the velocity profile in the logarithmic layer of “LES region” was deviated upward from the logarithmic law, which directly results in the Log-Layer Mismatch (LLM).

The key issue in this detached-eddy simulation methodology is how to eliminate the LLM phenomenon and thus various methods have been suggested so far. Hamba (2003) argued that the rapid spatial variation in the eddy viscosity from “RANS region” to “LES region” is responsible for an underestimate of Grid-Scale (GS) shear stress which eventually leads to the steep velocity gradient. Therefore, Hamba developed a new scheme to remedy the mean velocity mismatch. By introducing additional filtering, the GS velocity fluctuations became large enough and the two velocity components at the interface were free of mismatch. Considering the resolved eddies have not yet been generated in the transition region, Piomelli et al. (2003) introduced a backscatter model based on stochastic forcing to balance the global momentum. Later, Keating and Piomelli (2006) applied this kind of stochastic forcing model for WMLES in a dynamic computing manner. This approach successfully predicted the logarithmic layer and the velocity fluctuations. Abe (2005) also found that the shift up in the mean velocity profile is due to the underestimated of resolved shear stress. When the grid resolution is in the “danger zone” (Nikitin et al., 2000), the energy redistribution from the streamwise to the other two components is restrained, thus leads to overestimate of the streamwise turbulence and causes the drastic decrease of the resolved shear stress. Abe performed a nonlinear eddy-viscosity model to resolve the near-wall stress in the channel flows with various grid resolutions and at various Reynolds numbers. The calculations showed fairly good predictions of the mean velocity, turbulent energy and Reynolds shear stress. Davidson and Dahlström (2005) proposed a solution that adds turbulent fluctuations which are taken from a DNS simulation of a generic boundary layer to the momentum equations at the LES side of the interface. This approach is aimed at creating resolved turbulent structural information to “LES region” and can well predict the velocity profiles in the fully-developed channel flow. On the other hand, Travin et al. (2006) modified the Delayed Detached Eddy Simulation (DDES) to remove the LLM. Unlike the usual DES practice, they redefined the subgrid length-scale which includes both the wall-distance and the grid-spacing. In addition, an empirical function successfully blended the RANS and LES behavior, and greatly increases the resolved turbulent content near wall. Shur et al. (2008), further put forward a new hybrid model, IDDES, i.e. Improved DDES, which combines the DDES model with an improved RANS-LES hybrid model for WMLES using. The model showed that

mismatch error between the modeled log-layer and the resolved log-layer is eliminated in pure WMLES applications.

Even though many DES-like methods discussed above have predicted turbulent channel flows quite well, they contain much non-physical empiricism and thus some suffer from restrictions like grid aspect ratios, etc. Other than that, the applications of some models seem complex in certain extent. Therefore, there is a strong motivation to find a solution to repair LLM in DES without damaging the model accuracy and conciseness, and with as little empiricism as possible. Vreman (2004) put forward an eddy-viscosity subgrid-scale model. Instead of involving additional procedures like explicit filtering operations, ensemble averaging and clipping procedures, only the local filter width and the first-order derivatives of the velocity field are needed for the LES computation. Vreman model was proved to be more accurate than traditional Smagorinsky model in LES application (Smagorinsky, 1963), and actually as accurate as the dynamic Smagorinsky model (Germano et al., 1991). In the present study, we propose a new hybrid RANS-LES model which employs the Vreman eddy-viscosity subgrid-scale model in the “LES region” and applies the one equation SA model (Spalart and Allmaras, 1992) in the “RANS region”. The structural function in the Vreman LES model is used to switch on/off the LES computation according to whether the flow coherent structures appear or not. The present model is actually a variation of DES; we examine its performance via the simulations of turbulent channel flows and circular cylinder flows.

2. Model formulation

2.1. Vreman subgrid model

Vreman (2004) investigated the algebraic properties of the theoretical subgrid dissipation and provided a series of structural functions. The structural function that has the same algebraic property as the theoretical subgrid dissipation is treat as a good candidate to incorporate into the Vreman eddy viscosity. According to Vreman, the theoretical subgrid dissipation can be written as

$$D_\tau = -\tau_{ij}\alpha_{ij} = -\tau_{ij}S_{ij}, \quad (1)$$

where $\tau_{ij} = \overline{u_i u_j} - \overline{u_i} \overline{u_j} = -2\nu_t S_{ij} + \tau_{kk}\delta_{ij}/3$ is the SGS stress tensor, $\overline{(\bullet)}$ denotes the filtering operation, ν_t is the unknown eddy viscosity, and $S_{ij} = \frac{1}{2}(\partial_i \overline{u_j} + \partial_j \overline{u_i})$ is the strain rate tensor.

Provided that $\chi_{ij} = \partial_i u_j$ is the derivative matrix of unfiltered velocities, there exists 320 different kinds of χ by considering whether the first-order derivative is equivalence to zero or not, of course matrices that have precisely one nonzero diagonal element are not included (Vreman, 2004). The 320 types of matrices respectively represent 320 types of flows. Vreman divided them into ten groups based on the number of zero elements in the binary matrix. It is proved that the theoretical subgrid dissipation D_τ will vanishes for 13 types of derivative matrices. The structural function $\|S\|$ is closely related to the Smagorinsky eddy viscosity $(C_s \Delta)^2 |S|$ with $|S|^2 = 2\|S\|^2$, and it equals to zero only when the derivative matrix of velocities is a null matrix. However, the structural function B_β is found to be zero for 13 types of laminar flow mentioned above just like D_τ , thus it is able to act as the optimal candidate to incorporate into the eddy viscosity. The eddy viscosity proposed by Vreman is the following

$$\nu_t = c\Delta_m^2 \left(\frac{B_\beta}{\alpha_{ij}\alpha_{ij}} \right)^{1/2} \quad (2)$$

with

$$\alpha_{ij} = \partial_i \overline{u_j} = \frac{\partial \overline{u_j}}{\partial x_i}, \quad (3)$$

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