Detached-Eddy Simulation Based on the v^2-f Model

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Abstract: Detached eddy simulation (DES) based on the v^2-f RANS model is proposed. This RANS model incorporates the anisotropy of near-wall turbulence which is absent in other RANS models commonly used in the DES community. In LES mode, the proposed DES formulation reduces to a transport equation for the subgrid-scale kinetic energy. The constant, C_{DES}, required by this model was calibrated by simulating isotropic turbulence. In the final paper, DES simulations of canonical separated flows will be presented.

Keywords: detached eddy simulation, v^2-f model, hybrid RANS/LES

1 Introduction

Detached-eddy simulation (DES) is a hybrid RANS/LES approach that performs RANS in attached regions and LES in detached regions using a single model. In the LES region, the length scale of the RANS model is set proportional to the grid size Δ. The RANS model thereby becomes an LES model.

Although the Spalart-Allmaras (SA) model has been widely used for DES [1], its near-wall damping does not distinguish between velocity components. In contrast, the v^2-f formulation [2] models the suppression of wall normal velocity fluctuation caused by non-local pressure-strain effects. This anisotropy has been shown to improve prediction of separation and reattachment [3, 4]. In addition, the SA model uses the minimum distance to the wall as the turbulence length scale which is not necessarily accurate at or near separation. The v^2-f model, on the other hand, computes a length scale based on flow properties (i.e. the kinetic energy k, the dissipation rate ϵ, and the kinematic viscosity ν). Finally, in the LES region, the present treatment gives a transport equation for subgrid-scale (sgs) kinetic energy which is less empirical than the sgs viscosity transport equation used in SA based DES.

2 The Proposed v^2-f DES Model and Preliminary Results

The v^2-f formulation [2] has transport equations for k, ϵ and $\overline{v^2}$ and an elliptic relaxation equation for a function f analogous to the Reynolds stress redistribution term. These equations contain length and time scales L and T. The choice between RANS and LES modes is made by setting these scales appropriately. When the grid is fine enough to capture large turbulent eddies, i.e. when $C_{\mathrm{DES}}\Delta < k^{3/2}/\epsilon$, the LES mode is selected. Otherwise, the RANS mode is selected. As suggested by Spalart et al. [5], the DES coefficient C_{DES} is chosen to match the correct energy spectrum in isotropic turbulence. In LES mode, the time scale is obtained as $T = C_{\mathrm{DES}}\Delta/\sqrt{k}$ where k now represents the sgs kinetic energy. Although the k equation is sufficient for purely LES simulations, the other three equations are required for the RANS mode. The v^2-f model [2] is modified so that the entire set of the equations reduces to a transport equation for the sgs k in LES mode. In particular, coefficients in the elliptic relaxation equation are modified so that $\overline{v^2}$ becomes $(2/3)k$ in LES for isotropic turbulence. The final paper will include the formulation in detail.

To validate the modified coefficients, fully developed turbulent channel flows with friction Reynolds numbers Re_τ up to 2000 are simulated in RANS mode. Figure 1 shows that this modification maintains the performance of the unmodified RANS model with better prediction of $\overline{v^2}$ near the center. Next, to check the LES mode and calibrate C_{DES}, decaying isotropic turbulence is considered. The initial field uses 512^3 DNS data [6] at $Re_\lambda = 105$ filtered down to 32^3. Turbulence quantities in the DES model are initialized by running for some time with a frozen initial velocity field. The flow is allowed to run about eleven initial large-eddy turnover times at which point $Re_\lambda = 61$. The v^2-f DES simulation with $C_{\mathrm{DES}} = 0.8$ agrees very well with DNS [6] and experiments [7] (figure 2(a)) up to the cut-off wave number. Because it allows a higher Reynold number and a wider inertial range, forced isotropic turbulence at $Re_\lambda = 98$ is also considered using the stochastic forcing of Eswaran and Pope [8]. The v^2-f DES gives almost exactly the energy spectrum produced by the dynamic Smagorinsky model (figure 2(b)).

3 Conclusions and Future Work

DES based on the v^2-f model was proposed and validated for two cases: purely RANS and isotropic LES. These preliminary results are encouraging. The final paper will include DES simulations of the backward-racing step flow [9], and v^2-f based DES will be compared with SA based DES.

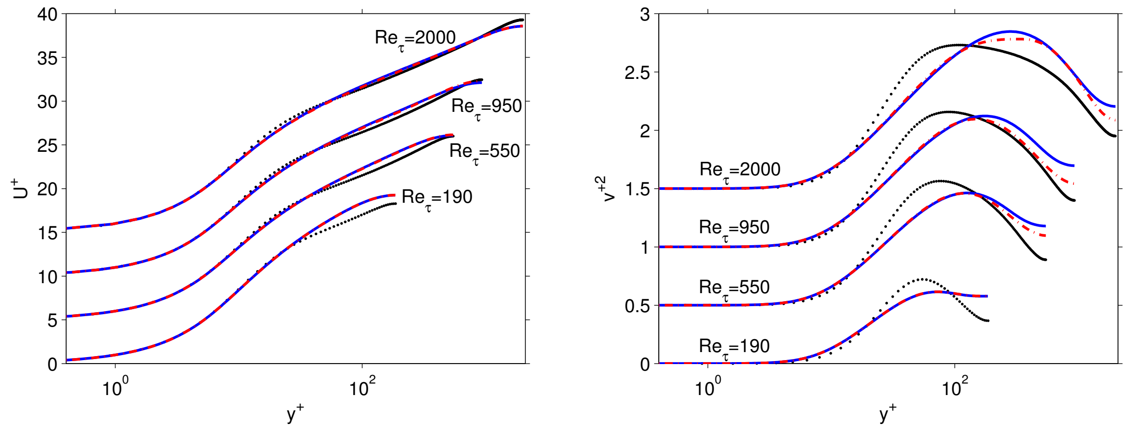
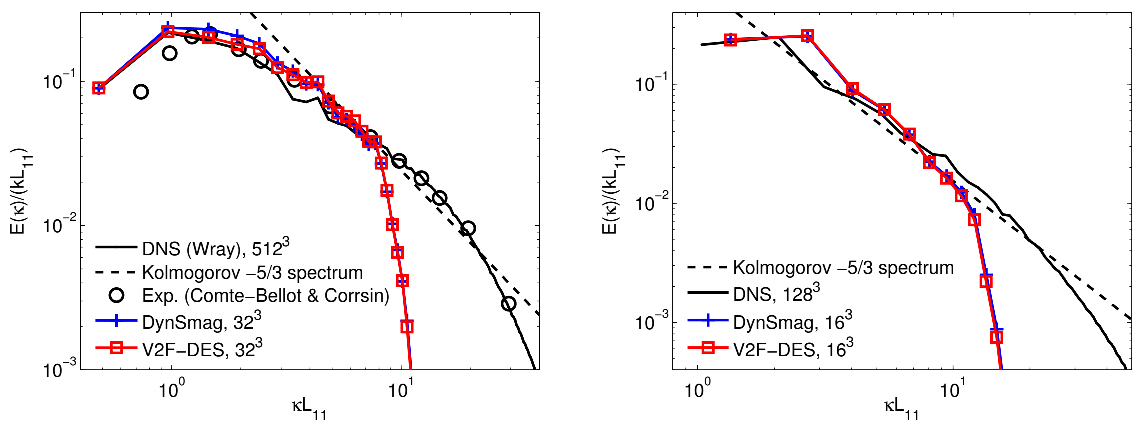


Figure 1: Profiles of U^+ and $\overline{v^{+2}}$ of DNS(dots) and RANS with the unmodified[2] (—) and the modified v2f model (-.-) in turbulent channel flows. The plus superscript indicates normalization with wall units.



(a) Decaying isotropic turbulence ($Re_\lambda = 61$).

(b) Forced isotropic turbulence ($Re_\lambda = 98$).

Figure 2: Energy spectrum of isotropic turbulence. The proposed DES model (V2F-DES) is simulated with $C_{\mathrm{DES}} = 0.8$. Kolmogorov -5/3 spectrum indicates $E(\kappa) = C\epsilon^{2/3}\kappa^{-5/3}$ with the Kolmogorov constant $C = 1.5$. DynSmag indicates LES with the dynamic Smagorinsky model.

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