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 $\Delta$. 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 $\epsilon$, and the kinematic viscosity $\nu$). 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 $k$, $\epsilon$ and $\sqrt{v^2}$ 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 $C_{DES}\Delta < k^{3/2}/\epsilon$, 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 $T = C_{DES}\Delta/\sqrt{k}$ 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 $\sqrt{v^2}$ 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 $Re_\tau$ 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 $\sqrt{v^2}$ near the center. Next, to check the LES mode and calibrate $C_{DES}$, decaying isotropic turbulence is considered. The initial field uses 5123 DNS data [6] at $Re_\lambda = 105$ filtered down to 323. 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 $C_{DES} = 0.8$ 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 $v'^+2$ 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.

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

References


