“Numerical Simulations and Analyses of Shock-Boundary Layer Interactions”

By

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Shock-boundary layer interaction (SBLI) is becoming one of the benchmark problems in the computational fluid dynamics (CFD) community. The interaction of shock wave with the boundary layer is a very complex phenomenon that requires high-fidelity numerical methods like direct numerical simulation (DNS) and large-eddy simulation (LES) to capture the flow physics. In this study, SBLI is examined for various flow conditions using DNS and LES.

In the first part of the study, DNS and LES of a flat-plate Mach 2 supersonic turbulent boundary layer interacting with an oblique incident shock wave were conducted for a priori and a posteriori assessments of subgrid-scale (SGS) models. The incident shock was strong enough to generate a marginal separation in the boundary layer near the interaction region providing the SGS models with a non-trivial challenge. The governing equations for DNS and LES were solved using a new seventh-order Monotonicity-Preserving scheme for inviscid fluxes and a sixth-order compact finite-difference scheme for the viscous terms. The effect of SGS stress term on the resolved velocity field was shown to be significant and shock-dependent. The subgrid-scale models tested included the mixed-time-scale model, the dynamic Smagorinsky model, the dynamic mixed model and a new dynamic model, termed the compressible serial decomposition model. A priori analysis indicated that the new dynamic model was more accurate than other SGS closures. A posteriori tests also indicated better predictions of DNS results by the LES employing the compressible serial decomposition model.

In the second part of this study, DNS computations were carried out for oblique shock/turbulent boundary layer interactions for a Mach 2.75 turbulent boundary layer and three different shock incidence angles. The numerical scheme used for the spatial discretization of Euler fluxes was a hybrid method that employed a high-order, non-dissipative central scheme in the shock-free regions and a fifth-order monotonicity preserving scheme in the shock regions. The accuracy of DNS calculations was established by checking for the convergence of the turbulent kinetic energy equation. Instantaneous flow visualizations showed the effect of shock on the downstream flow field. The separation bubbles exhibited highly unsteady nature and the maximum probability of flow separation was found to be independent of the shock strength. The differences between Reynolds- and Favre-averaged quantities were examined and observed to be largely independent of the shock intensity. Examination of the transport equations for turbulent kinetic energy and enstrophy showed that the compressibility effects were not very significant, even for the highest shock intensity. The DNS results will be made available on the web to aid in the development of LES and RANS models.

In the third part of this study, a priori estimates of various SGS terms in the compressible filtered Navier-Stokes equations were made using the highly accurate DNS database for the Mach 2.75 SBLI. The behavior of SGS stresses and also the components of SGS stresses, namely, Leonard, Cross and Reynolds, were examined in various regions of the flow for different filter widths. A term-by-term analysis of the SGS terms in the filtered total energy equations indicated that while each term was significant by itself, the net contribution by all the terms had a relatively small contribution and this was confirmed in the a posteriori analysis. The budgets for the SGS kinetic energy were examined with the aim of providing useful information for one-equation LES models. The backscatter in various regions of the flow was computed and was found to be significant only instantaneously.

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