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I. The subgrid scale modeling group

Subgrid-scale models are used in large-eddy simulation of turbulent flows, where the large-scale field is computed directly via the filtered Navier-Stokes equations and the small scale-field is modeled. The subgrid-scale model then represents the effects of the small scales on the large-scale motions. Relatively little effort has been devoted to subgrid scale modeling, despite its purported importance as an alternative to single-point closures for solving engineering problems. The Smagorinsky (1963) model remains as the most widely used model for large-eddy simulations. Several modifications to this model have been proposed to account for mean-flow complexities, but they are generally based on *ad hoc* foundations. Improvements have also been sought in analogy with single-point closure models by using moment equations for the subgrid-scale stresses (Deardorff, 1973, *J. Fluids Eng.* **95**; Schumann, 1975, *J. Comp. Phys.* **18**).

The key element that has been missing in most subgrid scale modeling efforts has been the effective utilization of the large-scale field which is computed directly. This rather rich spectral information is not available in methods based on Reynolds-averaged equations and should be brought to bear in large eddy simulations. The model of Bardina *et al.* (1980, *AIAA 80-1357*) is a rare example where an attempt is made to extrapolate from the computed large-scale field to model the small scales; however, this model still relies on a supplementary Smagorinsky model to provide the necessary subgrid-scale dissipation. Several improved subgrid-scale models have been developed in Fourier space based on statistical theories of homogeneous turbulence. Although they are appealing because of their more rigorous theoretical foundations, they are of little use for inhomogeneous flows, where the problems are formulated in physical space, and where accurate subgrid-scale models are really needed.

The problems with the Smagorinsky model (or its variants) are: 1) The optimal model constant must be changed in different flows; 2) the model does not have the correct limiting behavior near the wall; 3) the model does not vanish in laminar flow, and it is demonstrated to be too dissipative in the laminar/turbulent transition region; 4) the model does not account for backscatter of energy from small scales to large scales, which has been shown to be of importance in the transition regime; and 5) compressibility effects are not included in the model. The objective of the subgrid-scale modeling group was to address these issues.

The group concentrated on four projects: Three were devoted to the development, implementation, and testing of subgrid-scale models, and one was an attempt to quantify the subgrid-scale backscatter using direct numerical simulation databases. Germano, Piomelli, Moin & Cabot used the scale-similarity ideas of Bardina *et al.* and Germano (1990, *CTR Manuscript 116*) to derive an eddy viscosity model. The model uses the strain fields at *two different scales* and thus utilizes spectral information in the large-scale field to extrapolate the small-scale stresses. Using an algebraic identity derived by Germano (1990), and using the Smagorinsky model to

represent the subgrid-scale stresses at both scales, an expression for the Smagorinsky "constant" is derived which is a function of space and time. The constant can be negative in some regions and thus does not totally exclude backscatter, it provides for the proper asymptotic behavior of the stresses near the wall without *ad hoc* damping functions, and it vanishes in laminar flow without *ad hoc* intermittency functions. Large-eddy simulations of the transitional and turbulent channel flows using this model performed during the Summer Program were very encouraging. Essentially, the agreements with the direct simulation results were as good or better than those obtained with variants of the Smagorinsky model but without the fine-tuning and the *ad hoc* components that such models have required. I believe that this model represents a major advance in subgrid-scale modeling and should be tested in more complex turbulent flows.

Eddy viscosity models are absolutely dissipative; that is, energy is transferred from large scales to the small scales. Although this is the correct behavior in the mean, it is not necessarily true instantaneously and at each point in space. In fact, recent computations by Piomelli *et al.* (1990, *Phys. Fluids A*, **2**) have indicated that backscatter may be dynamically critical in the transition region. Piomelli, Cabot, Moin & Lee investigated the scope of backscatter using direct numerical simulation databases of turbulent and transitional channel flow and compressible isotropic turbulence at different Reynolds numbers and Mach numbers. It was very surprising to find that at any instant about 50% of the grid points were in the state of energy transfer from small to large scales when sharp cut-off filters were used. Although the mean transfer is from large to small scales, it results from the small difference between large forward and backward components.

Comte, Lee & Cabot tested and modified the structure-function-based model of Métais & Lesieur (1990, preprint). The main appeal of the model is its rigorous roots in wave space. The model is formulated in physical space, however, and is directly applicable to inhomogeneous flows. It was tested using the database from direct numerical simulation of channel flow. Its asymptotic behavior near the wall was not correct and modifications were implemented to improve it. This model was also incorporated in a large-eddy simulation of compressible isotropic decay, and, as expected, its performance was satisfactory.

Squires & Zeman developed an eddy viscosity model for compressible flows. The model is essentially a modification of the Smagorinsky model with a parameterization of turbulence kinetic energy that must now be accounted for separately. In the limit of incompressible flow, the Smagorinsky model is recovered. They also obtained an expression for the eddy diffusivity *tensor*. The stress-similarity ideas of Germano *et al.* can be applied in a straightforward manner to this model for dynamic computation of the space- and time-dependent model coefficient. This extension to the model of Squires & Zeman should provide an attractive subgrid-scale model for compressible flows. Other improvements would be to account for the effects of eddy shocklets. Some ideas in this direction are presented by Squires & Zeman, but they have not been tested.

<div align="right">Parviz Moin</div>