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Guest Editorial

Alternative LES and Hybrid RANS/LES for Turbulent Flows

After more than 30 years of intense research on large-eddy simulations (LES) of turbulent flows based on eddy-viscosity subfilter models, [1], there is now consensus that such an approach is subject to fundamental limitations. It has been demonstrated for a number of different flows that the shear stress and strain tensors involved in subfilter eddy-viscosity models have different topological features rendering scalar eddy-viscosity models inaccurate. There have been other proposals that do not employ the assumption of colinearity of strain and stress embedded in the eddy-viscosity models, e.g., the scale-similarity model of Bardina [2]. However, such models are numerically unstable, and more recent efforts have focused on developing mixed models, combining in essence the dissipative eddy-viscosity models with the more accurate but unstable scale-similarity models. The results from such mixed models have been mostly satisfactory but the implementation and computational complexity of the combined approach have limited its popularity.

Recognizing the aforementioned difficulties but also motivated by new ideas pioneered at the Naval Research Laboratory by Jay Boris, several researchers have abandoned the classical formulation and started employing the original, unfiltered, Navier-Stokes equations (NSE) instead of the filtered ones. In this case, one could use *ab initio* scale separation with additional assumptions for stabilization, or invoke monotonicity via nonlinear limiters that implicitly act as a filtering mechanism for the small scales. The latter was the original proposal of Boris et al. [3] in the early 1990s, although as a concept it goes back to von Neumann and Richtmyer, who were working on explicit artificial dissipation schemes. It was actually this concept that also motivated Smagorinsky [4] in developing his model. An intriguing feature of the monotonically integrated LES (or MILES) approach, [3], is the activation of the limiter on the convective fluxes and its role in generating *implicitly* a tensorial form of eddy-viscosity that acts to stabilize the flow and suppress oscillations.

Today development of more sophisticated subgrid scale (SGS) models is actively pursued, and *alternative* nonclassical formulations are being developed. The features of the new LES models can be investigated based on the partial differential equations satisfied by the numerical solution—the modified LES equations, which reveal the competing effects of discretization and explicit SGS modeling. From this perspective, *all* numerical schemes provide a built-in *implicit* SGS model effectively enforced by the leading order discretization errors. The modified LES equations' analysis can likewise be used to address the extent to which a specific *implicit* SGS model might be adequate by itself when suitable algorithms are used, or when additional filtering and/or approximate deconvolution procedures are included as part of the overall LES approach.

For turbulent flows of industrial complexity the Reynolds-averaged Navier-Stokes (RANS) equations, with averaging typically carried out over time, homogeneous directions, or across an ensemble of equivalent flows has been employed. Additional semi-empirical information on the turbulence structure and its relation to the mean flow may also be required depending on the variant of the RANS model. A new trend, which had a fair amount of success, is to combine RANS with LES in order to exploit the best features of both approaches in a complementary manner. LES is capable of simulating flow features which cannot be handled with RANS, such as significant flow unsteadiness and strong vortex-acoustic couplings. However, this added capability carries a high computational cost—at least an order of magnitude more expensive than RANS, and it is a particularly important problem when LES is applied to the entire flow domain. As a consequence, *hybrid* RANS/LES approaches have been developed restricting the use of LES to flow regions where it is crucially needed while using RANS elsewhere. Such developments are thought to be particularly effective for practical flow configurations.

These new advances both on the LES as well as the RANS fronts have attracted a lot of interest recently and have comprised a special focus of several workshops and conferences. Four well attended invited sessions on ''Alternative LES and Hybrid RANS/LES'' addressing this timely subject were organized by one of us (F.F.G.) at the 40th AIAA Aerospace Sciences Meeting at Reno, NV, Jan. 14–15, 2002. Thirteen selected papers from those sessions are included in this special issue of JFE: The first nine are devoted to alternative LES formulations, and the following four to hybrid RANS/LES.

In the *first paper*, Domaradzki and Radhakrishnan use concepts from their SGS estimation modeling approach to develop an LES procedure which employs the NSE truncated to an available mesh resolution. Operationally, the procedure consists of numerically solving the truncated NSE and a periodic processing of the small-scale component of its solution. The use of this approach is exemplified by simulations of Raleigh-Bénard convection. In the *second paper* Von Kaenel et al. describe their approximate deconvolution model for LES based on a second-order finite volume scheme, in which an approximation of the unfiltered solution is obtained by repeated filtering, and given a good approximation of the unfiltered solution, the nonlinear terms of the NSE are computed directly. The effect of scales not represented on the grid is modeled by a relaxation regularization involving a secondary filter operation. Simulations of a supersonic turbulent channel flow with this approach are presented. In the *third paper*, Visbal and Rizzetta describe an LES approach on curvilinear grids combining the use of 4th and 6th-order compact differencing and 10th-order low-pass Padé-type filtering schemes. The performance of their approach is illustrated in the simulation of decaying compressible isotropic turbulence and turbulent channel flow.

In the *fourth paper*, in the monotonically integrated LES (MILES) approach, Grinstein and Fureby focus on the unfiltered NSE and on emulating (near the LES cutoff), the high-wave-number end of the inertial subrange region—characterized by thin filaments of intense vorticity embedded in a background of weak vorticity. This motivates using numerical (flux-limiting) schemes incorporating a sharp velocity-gradient capturing capability operating at the smallest resolved scales. A formal analysis of MILES is carried out based on the modified equations and applications discussed include both free and wall-bounded flows. In the *fifth paper*, Margolin et al. demonstrate the effectiveness of monotonicity (sign) preserving formulations by arguing that the leading order truncation error introduced by nonoscillatory finite volume schemes represents a physical flow regularization term, providing necessary modifications to the governing equations that arise when the motion of *observables*—finite volumes of fluid convected over finite intervals of time—is considered. Their analysis is based on Burgers' equations and the modified equations, and illustrated with simulations of fully developed turbulence. In the *sixth paper*, Yan et al. report the first LES predictions of heat transfer in adiabatic and isothermal supersonic flat-plate boundary layers using the MILES technique.

In the *seventh paper*, the basic modeling idea in the simulation method presented by Fan et al. is similar to that used in shock capturing, where intrinsically discrete equations are satisfied in thin modeled regions. Their vorticity confinement method does not attempt to accurately discretize the flow equations, but, rather, serves as an implicit nonlinear model of the vortical structures directly on the grid, where structures at the smallest scales (~ 2 grid cells) are captured and treated effectively as solitary waves. Applications presented include simulations of flows over round and square cylinders and a realistic helicopter landing ship. In the *eighth paper*, Kirby and Karniadakis present an overview of their spectral vanishing viscosity (SVV) method and its proper use in achieving monotonicity without changing the formal (spectral) accuracy of their discretizations. Some new enhancements of the technique presented here include a new SVV filtering for the continuous Galerkin method in which filtering is accomplished on a fully orthogonal set of modes, and a proposed new method to compute adaptively the viscosity amplitude according to the local strain. Results for turbulent incompressible channel flow are presented to illustrate the application of the method. In the *ninth paper*, Persson et al. consider the homogenization method as alternative to the filtering approach fundamental to conventional LES; it consists of finding a so-called homogenized problem—i.e., finding an homogeneous ''material'' whose overall response is close to that of the heterogeneous ''material'' when the size of the inhomogeneity is small. The authors develop an homogenization-based LES model using a multiple-scales expansion technique and taking advantage of the scaling properties of the NSE. This method is used to simulate forced homogeneous isotropic turbulence and turbulent channel flow, and results are compared with available DNS results and laboratory data.

In the area of hybrid RANS-LES, in the *tenth paper*, Constantinescu et al. present prediction of the flow over a prolate spheroid using the detached-eddy Simulation (DES), in addition to solutions obtained from of the unsteady RANS equations. The study offers the opportunity to gain some insight into application of DES to a complex flow experiencing smooth-surface separation and to also assess corrections for streamline curvature and a nonlinear constitutive relation applied to the underlying RANS model. In the *eleventh paper*, Forsythe et al. computed the supersonic flow around a missile base using DES along with several RANS models. This work offers an opportunity to compare DES and RANS predictions against experimental measurements in a compressible flow, allowing assessment of corrections to the RANS models for compressibility. Predictions of the base pressure and structure of the wake are among the results that are presented.

In the *twelfth paper*, Morton et al. use DES to predict the flow over a delta wing at 27 deg angle of attack, contrasting the calculations against unsteady RANS predictions that include corrections for streamline curvature. A key feature of the configuration and a challenge to models is prediction of vortex burst over the wing. Results of the flow structure are presented along with quantitative comparison to experimental measurements of kinetic energy levels in the vortex core. In the *thirteenth and final paper*, Fasel et al. apply a hybrid RANS-LES approach coined as ''Flow Simulation Methodology'' in which a contribution function is introduced to delineate the level of predicted stress that is modeled and resolved. Application of the method to wall-bounded and open flows is presented.

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