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Book Reviews

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Large Eddy Simulation for Incompressible Flows, An Introduction, 3rd Edition

Sagaut, P., Springer–Verlag, New York, 2006, 556 pp, $89.95

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This new edition of Pierre Sagaut's large eddy simulation (LES) book is timely and extremely welcome in the fluid dynamics community. Compared to the second edition, which appeared two years earlier, the original material has been expanded by 130 additional pages and the relevant literature survey now lists more than 800 references. Significantly new material in a number of important areas has been added to increase coverage of this fast-growing and challenging field of turbulent flow simulations.

Turbulent flows are of considerable importance in many applications in aerospace engineering, geophysics, and astrophysics. High-Reynolds number turbulent flows involve a broad range of length and time scales. The largest scales are related to the specific geometry, boundary conditions, and regimes considered, and the smallest are associated with the dissipation of turbulent energy through viscosity. A predictive closed theory of turbulent flows has not yet been established and is unlikely to emerge in the foreseeable future. Moreover, it is not possible to compute most high-Reynolds (*Re*) number turbulent flows by direct numerical simulation (DNS) resolving all relevant scales in space and time. Instead, at least part of the unsteady turbulent motion must be approximated to make these calculations feasible.

Numerical simulations involve the discretization of the conservation flow equations on computational grids having finite resolution and dimensions. Relevant issues that need to be addressed relate to the modelling of unresolved *subgrid* scale features (within a computational cell) and at the *supergrid* level (beyond computational boundaries); such information must be prescribed for closure of the equations solved numerically. Subgrid models act (explicitly and/or implicitly) as additional source terms in the actual equations solved by the solutions being calculated. Supergrid models provide the necessary set of initial and boundary conditions that must be prescribed to ensure unique well-posed solutions.

The grand challenge is to develop simulation models that, although they may not be explicitly incorporating all dynamic scales, will still give accurate and reliable results for at least the larger energy-containing scales of flow motion. The Reynolds-averaged Navier–Stokes (RANS) equations, with averaging typically carried out over time, homogeneous directions, or across an ensemble of equivalent flows, have been employed for turbulent flows of industrial complexity. LES has become the effective intermediate approach between DNS and RANS, capable of simulating flow features that cannot be handled with RANS, such as significant flow unsteadiness and strong vortex-acoustic couplings, and providing higher accuracy than RANS at a reasonable cost. The main assumptions of LES are as follows: 1) transport is largely governed by large-scale unsteady features, and such dominant features of the flow can be resolved in space and time; and 2) the presumably less-demanding (i.e., universal and large-scale independent) accounting of the unresolved smaller-scale flow features can be undertaken by using suitable subgrid scale (SGS) models.

The relevant aspects of model approximation levels and scale separation are addressed by Sagaut in the introductory Chapter 1. This new Chapter 1 appears enriched by an overview of the structure of the book and a very insightful analysis of the critical competition of *uncertainties* due to projection, discretization, and resolution when simulating turbulent flow with LES. A very good discussion of the mathematical formulations of scale separation and closure issues is given in Chapters 2 and 3, respectively, and the various attempted SGS modeling strategies are introduced. It is crucial to note here that, in the absence of an accepted universal theory of turbulence, the development and improvement of SGS models are unavoidably pragmatic and based on the rational use of empirical information. Moreover, a universal definition of LES is also not well established. Thus, it is very important for the reader hoping to learn about the "best" LES modeling approach to have the conventional wisdom of what is traditionally postulated and/or assumed stated up front in an unbiased form, and Sagaut manages to do this in a very attractive and consistent fashion. Various classical and nonclassical approaches to functional and structural SGS modeling are extensively covered in Chapters 4–7. A new section dealing with alternative mathematical formulations of LES (Chapter 4) includes the ensemble-averaged and regularized Navier–Stokes models.

The *functional* SGS model proposals, for which *the actions* of the SGS stress τ on the filtered velocity (rather than modeling the SGS stress itself) are modeled to represent kinetic energy transfers, are presented in their isotropic (Chapter 5) and anisotropic (Chapter 6) versions. Both the forward and backscatter cascade modeling problems are very well addressed in this context, and a new extended discussion of dynamic, structure-function, and multiscale models has been added. Within the section of forward cascade modeling (Chapter 5), Sagaut also reports on nonclassical implicit SGS modeling efforts, based on employing the raw (unfiltered) flow equations instead of the filtered ones. Several nonconventional approaches are discussed, namely the implicit LES concept (ILES), adaptive flux reconstruction, and variational schemes with embedded subgrid stabilization. The major focus of these new approaches has been on the inviscid inertial-range dynamics and regularization of the underresolved flow based on ab initio scale separation with additional assumptions for stabilization, or building physical constraints via nonlinear limiters that implicitly act as filtering and regularizing mechanisms for the small scales—the underlying concept supporting ILES. The use of numerical dissipation to stabilize finite-difference simulations of flows involving shocks goes back to the 1950s, to von Neumann and Richtmyer. The artificial dissipation concept also motivated Smagorinsky in developing his scalar eddy-viscosity concept in the early 1960s, based upon the principles of similarity in the inertial range of 3-D isotropic turbulence. Interestingly, shock capturing and LES methods share not only their common start but also their later evolution focusing on flow-adaptive (dynamic) strategies. However, the recognition and formalization of the ILES property dates to later work starting in the 1980s (comprehensively described recently in *Implicit Large Eddy Simulation, Computing Turbulent Flow Dynamics*, Cambridge).

The more sophisticated *structural* models (based on modeling the subgrid tensor τ itself) are discussed in Chapter 7. The presentation includes models based on the scalar similarity hypothesis, approximate deconvolution approaches based on using series expansion approximations to the formal inverse-filtering operation, implicit structural approaches, and mixed models that, in essence, combine dissipative functional models with the more accurate but typically unstable structural formulations. Important additions in this chapter are new sections on filtered-density-function and multiscale models.

Sagaut discusses the important issues of the dynamic interpretation of LES, the competition between numerical and explicit SGS modeling, and provides some remarks on the use of artificial dissipations in Chapter 8. Closely related aspects of the analysis and validation of LES data are examined in Chapter 9. Adding to the inherent physics-based difficulties in developing and validating SGS models, truncation terms due to discretization are comparable to SGS models in the typical LES strategies, and LES resolution requirements can become prohibitively expensive for practical flows and regimes (Chapter 8). In fact, because of the need to distinctly separate (i.e., resolve) the effects of explicit filtering and SGS reconstruction models from those implicitly due to discretization, carrying out a *well-resolved* (i.e., discretization-independent) LES can typically amount in practice to performing *coarse* DNS. These practical difficulties motivated some of the nonclassical approaches discussed previously, for example, ILES—focusing on SGS modeling and filtering provided implicitly by *physics capturing* numerics (Chapter 5) and the coupling of LES with multiresolution/multidomain techniques (surveyed in Chapter 11), as well as new trends combining RANS with LES to exploit the best features of both approaches in a complementary manner in the so-called hybrid RANS/LES (discussed in Chapter 12)—which might be unavoidable strategy in the foreseeable future for realistic whole-domain complex configurations.

Although SGS modeling issues have motivated intense research in the last thirty years, comparatively less attention has been devoted to the equally relevant supergrid modeling aspects, and their importance is often overlooked. Because actual boundary condition choices *select* flow solutions, emulating particular flow realizations demands precise characterization of their initial (e.g., inflow) and other relevant (e.g., of asymptotic flow, or at solid and facility boundaries) conditions. The flow characterization issue is a challenging one when laboratory realizations are involved in LES model validation, because the reported laboratory information is typically insufficient and/or inadequate. Achieving closure of the supergrid model based on laboratory data requires identifying appropriate data acquisition and its suitable postprocessing for use in LES. Chapter 10 presents a very thorough presentation of supergrid modeling issues relevant to LES, with particularly good special focus on those for modeling turbulent inflow and wall boundary conditions.

Practical LES implementation issues discussed by Sagaut in Chapter 13 focus on cutoff length computation procedures, discrete test filters for use in computing SGS models or in prefiltering techniques, and the computation of structure function models on an arbitrary grid. Chapter 14 is then devoted to discussing representative examples of applications, including homogeneous turbulence, flows with a direction of inhomogeneity, flows with at most one direction of homogeneity, and industrial applications; the chapter concludes with an interesting *lessons learned* section. Chapter 15, which is dedicated to the analysis of the coupling of flow and scalars in LES, is Sagaut's most significant addition, given its considerable timely interest for complex engineering and geophysical flow applications. The chapter addresses critical SGS mixing modeling issues for passive scalars, as well as those relevant when active scalars in stable or unstable stratified flows are involved. Finally, useful Appendices on "Statistical and Spectral Analysis of Turbulence" and "EDQNM Modeling" help ensure the self-contained nature of the volume.

Pierre Sagaut's book, *Large Eddy Simulation for Incompressible Flows*, presents a systematic broad perspective of the state-of-the-art of LES. I very highly recommend it as of fundamental interest to graduate students and basic research scientists, as well as to professionals involved in the design and analysis of complex turbulent flows.

Fernando F. Grinstein
Los Alamos National Laboratory