Preface

The flow of fluids plays an important role in many technological and natural systems. A detailed knowledge of the dominant mechanisms is often essential in order to understand the functioning of these systems and to be able to optimize specific aspects. The large diversity of basic phenomena associated with fluid-flows makes this field of study both intriguing and challenging, while the variety of applications adds to the vitality and scope.

Modern simulation strategies for turbulent flow are more and more focused on capturing the generic features of the unsteady flow through computation rather than to aim for a complete statistical modeling of the relevant fluctuation-correlations as in a Reynolds averaged Navier-Stokes approach. A major step in the simulation approaches incorporates a smoothing and regularization of the dynamical complexities of the full evolution equations through some form of explicit or implicit filtering. In several different ways, this smoothing gives rise to a closure problem and consequently introduces the element of modeling into the simulation strategy. To complete the simulation approach, a physically relevant numerical representation of the basic governing conservation principles has to be created leading to a viable computational dynamical system with which the properties of the fluid flow are mimicked to varying degree.

The strategy of smoothing, modeling and numerical representation has different realizations. At one extreme, the element of smoothing of the dynamics and the influence of the numerics is minimized and a truthful and complete representation of the full equations is the final goal. This direct numerical simulation (DNS) approach is complemented by large-eddy simulation (LES) which allows a continuous perturbation of the original evolution through the introduction of a new, externally specified length-scale that governs the amount by which the dynamics is smoothed. In order to be effective, the new length-scale is usually much larger than the smallest turbulent length-scales in the flow, and smoothing induces a substantial reduction in the effective degrees of freedom. This leads to a sizeable deviation between the LES predictions of the smallest retained-scales and DNS predictions of flow-features with the same scales, while the smoothing effect may be much more modest for a number of ‘derived’ flow properties such as mean-flow and fluctuation predictions. Simultaneously, the smoothing allows for simulations at much reduced computational cost and increases the physical parameter-range for which simulations are feasible. This is one of the virtues of LES.

The search for a proper and acceptable balance between the reduction of information content in the smoothed representation on the one hand while retaining sufficiently accurate predictions in a given application area on the other hand is at the heart of modern simulation strategies for turbulent flow. They form a recurring theme in this book and express themselves e.g. in developments and further understanding of the modeling process, use of accurate numerical methods with a better understanding of the dynamical consequences of numerics in relation to the resulting computational dynamical system and application of these strategies in more and more complex physical situations including the confrontation with experimental and theoretical findings.

The material which is compiled in this book has arisen from an initially much more modest attempt to put together a special issue of the ERCOFTAC Bulletin in association with the Large-Eddy Simulation interest group (LESig). The call for contributions that was sent out, received such a positive and stimulating response that it was decided to compose a more complete and coherent exposition of the prominent trends and developments that can be distinguished in relation to modern strategies for turbulent flow simulation. Attention is paid to elements such as modeling the dynamic consequences of small 'universal' features in a turbulent flow as well as their numerical representation and treatment which incorporates numerical discretisation methods, suitable boundary conditions and an understanding of the dynamic interaction between the various sources of error that are present in any simulation approach to turbulence.

The main promise of LES is to provide the 'same' predictions for low-order statistical quantities and general flow dynamics as arise from DNS, however at strongly reduced computational effort. Stated differently, LES is supposed to predict turbulent flows at conditions and/or geometry complexities which are presently not accessible to a full DNS. Of course such a promise has a 'price'. Major problems associated with LES of turbulent flow are encountered in the form of a closure problem for the subgrid-scale stresses, geometry complexities, e.g. wall proximity or strong spatial inhomogeneity, and numerical treatment at marginal resolution.

This book is grouped in two parts. The first part comprises Chapters 1 – 9 and focuses mainly on subgrid modeling and on theoretical developments which put subgrid modeling in a broader context and furnishes connections with turbulence theory. The second part is dedicated to physical and numerical aspects arising from the application of direct- and large-eddy simulation in a number of different fields of interest. This material is contained in Chapters 10 – 16.

The first part of the book which deals with various aspects of modern subgrid model development begins with a short review. In Chapter 1, Sandham describes a picture of the state-of-the-art in direct and large-eddy simulation as has arisen from the Turbulence program at the Isaac Newton Institute in Cambridge (UK) in 1999. The subgrid-model developments reported in Chapters 2 – 5 are all characterized to some extent by approaches which attempt to make optimal use of the information contained in the resolved scales. This is inspired by the desire to reduce the element of physical intuition in subgrid modeling. It involves formulations in which some form of additional direct or indirect smoothing of the dynamics e.g. by means of eddy-viscosity contributions or additional regularizations is present. This careful balance between representing 'similarity' properties of the turbulent stress tensor and energy-transfer between grid-scale and subgrid-scale flow features is realized in various different ways in the contributions in these chapters.

Adams and Stolz present a 'deconvolution' approach in chapter 2 which aims at (partially) reconstructing the unfiltered information about a flow-field from the filtered prediction which arises from the simulation. This procedure as well as the need and role of additional regularization is exposed. A different approach is considered by Yee and Domaradzki in chapter 3 in which the subgrid-scale estimation model is presented and applied to decaying homogeneous turbulence. In this model, the modes contained in the resolved solution are used at every time-step to estimate the magnitude of modes that are not contained explicitly. This procedure involves as main step an interpolation, which may cause some unphysical properties of the estimated small scales. An additional relaxation procedure which allows a rapid 'settling' of the smaller estimated scales completes this model. The reconstruction of small scale information required for the turbulent stress tensor, by means of low order Taylor expansion, is at the heart of the velocity increment model which is presented in Chapter 4 by Brun and Friedrich. Through the introduction of an additional dynamic coefficient the velocity increment model is shown to lead to stable simulations of turbulent pipe flow up to Reynolds numbers of 520 (based on friction velocity). A closely related model arises from approximate, low-order reconstruction in Chapter 5 by Winckelmans et al. who follow the explicit filtering approach to LES. The resulting 'tensor-diffusivity' model can lead to stable simulations by itself providing backscatter as well as global dissipation. A combination with a dynamic eddy-viscosity leads to an appealing 'mixed model'.

In Chapters 6 – 8 the subgrid-modeling is considered from various, more theoretical directions. Domaradzki and Holm study the Navier-Stokes-alpha modeling approach to turbulence in Chapter 6. This arises from a 'regularized' version of the Kelvin circulation theorem for inviscid fluid flow. A direct connection is made with the familiar LES formulation leading to a clear identification of new subgrid models which involve nonlinear dispersion. These models are shown to generalize similarity models and the transformation properties of these models are investigated. In Chapter 7, Horiuti investigates consequences for subgrid modeling that arise from imposing basic transformation properties of the filtered equations. Preserving rotational transformation properties has some direct implications for a number of subgrid models and removes some of the ad hoc assignment of model-parameters. In addition, the coherent vortical structures that contribute most to the energy transfer between grid-scale and subgrid-scale flow features were identified using a new classification method. In Chapter 8 a review of renormalization methods for turbulence simulation is provided by McComb. The role of an effective viscosity in relation to the dissipation rate is considered and a direct procedure to prevent unphysically high levels of small-scale features in an incompletely resolved simulation is put forward. This procedure can be interpreted in terms of an associated effective scale-dependent eddy-viscosity which regularizes the simulation. The interactions between flow-features of different size is discussed in the context of local energy transfer theory.

The subgrid modeling part of this book is completed by a personal view of Germano in Chapter 9 in which developments in the dynamic modeling procedure are put in an historic perspective and options for extensions of this approach are discussed, together with recent advances which involve a combination of ‘inverse modeling’ or ‘deconvolution’ approaches and the dynamic procedure.

The second part of the book is devoted to a larger extent to application of the direct and large-eddy simulation approach. Of course, in many of these contributions there are also elements of subgrid modeling and the distinction with the first part of the book is not completely clear-cut. Roughly speaking, the developments in subgrid modeling that occur in these chapters are more focused on requirements posed by the particular additional complexities of the applications which are addressed. Moreover, the role of DNS in relation to a systematic development of LES is illustrated in several cases.

In chapter 10, Härtel et al. present a direct simulation study of the instabilities that are responsible for the detailed evolved structure of density-driven gravity-current heads. A close comparison with linear stability theory facilitates further identification of the dominant mechanism which appears closely connected to unstable stratification effects near the head.

The important problem of wall-modeling in the context of LES is addressed in Chapter 11 by Diurno et al.. The basic problem is put into perspective and a two-layer model is put forward in which the near-wall region is treated with the Spalart-Allmaras RaNS type-model whereas the outer region follows a conventional LES involving a localized dynamic eddy viscosity subgrid model. Predictions for the backward-facing-step are encouraging.

The desire to approach flows with a strongly increased complexity, in order to develop LES for flows of engineering interest, is one of the basic motivations behind the Very Large Eddy Simulation strategy (VLES) which is described in Chapter 12 by Hanjalić and Kenjereš. In this approach a merging of Reynolds averaged modeling and unsteady flow predictions is advocated. This approach is illustrated with an application in which the combined effect of thermal buoyancy and magnetic fields influence the flow.

In present-day studies the increase in computational capabilities is used more and more to incorporate additional physical phenomena into the simulation approach. An example of this is the study by Bastiaans et al. in Chapter 13 in which DNS of non-premixed combustion is considered and illustrated with the geometrically simple ‘canonical’ flow in a mixing layer. This allows for an investigation of the interaction between small-scale turbulent flow features and associated chemical reactions. A further application of DNS and LES to the investigation of turbulence-combustion interaction is contained in Chapter 14 by Luo. A complete formulation of the governing filtered equations is presented and DNS and LES studies of combustion in both low-speed and high-speed flow are presented, identifying the role of appropriate subgrid modeling of the strongly nonlinear and spatially highly localized chemical source terms.

Another application of LES is contained in Chapter 15 by Boersma in which the problem of acoustics in turbulent jets is addressed, taking into account the effects of compressibility in the filtered equations in a direct manner which avoids Favre averaging. The use of appropriate high order numerical methods is advocated in order to separate numerical from subgrid dissipation.

Finally, in chapter 16, Geurts and Fröhlich address the numerical contamination of LES of a turbulent mixing layer and identify suitable ratios between filter-width and grid-spacing which allow for a clear separation of numerical and modeling effects. The concept of 'grid-independent LES' is introduced and confronted with its desirability and with the associated computational costs required to realize such simulations.

At the completion of this preface I would like to acknowledge the positive and fruitful interaction I have had with all the participating authors. This has made the task of editing the manuscripts very stimulating and I hope that some of the enthusiasm which is underneath all of this, will be an inspiration for future developments.

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