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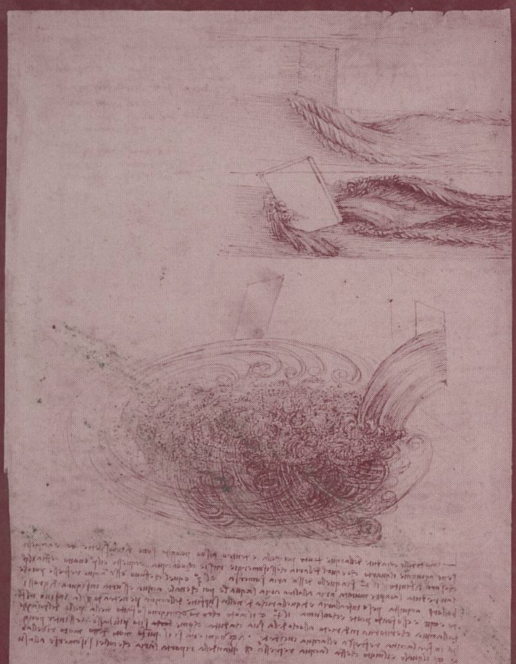
Modeling Complex Turbulent Flows



Edited by

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MODELING COMPLEX TURBULENT FLOWS

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① Turbulence –
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PREFACE

Turbulence modeling both addresses a fundamental problem in physics, 'the last great unsolved problem of classical physics,' and has far-reaching importance in the solution of difficult practical problems from aeronautical engineering to dynamic meteorology. However, the growth of supercomputer facilities has recently caused an apparent shift in the focus of turbulence research from modeling to direct numerical simulation (DNS) and large eddy simulation (LES).

This shift in emphasis comes at a time when claims are being made in the world around us that scientific analysis itself will shortly be transformed or replaced by a more powerful 'paradigm' based on massive computations and sophisticated visualization. Although this viewpoint has not lacked articulate and influential advocates, these claims can at best only be judged premature. After all, as one computational researcher lamented, 'the computer only does what I tell it to do, and not what I want it to do.'

In turbulence research, the initial speculation that computational methods would replace not only model-based computations but even experimental measurements, have not come close to fulfillment. It is becoming clear that computational methods and model development are equal partners in turbulence research: DNS and LES remain valuable tools for suggesting and validating models, while turbulence models continue to be the preferred tool for practical computations.

We believed that a symposium which would reaffirm the practical and scientific importance of turbulence modeling was both necessary and timely. This belief led to the ICASE/LaRC/AFOSR Symposium on Modeling Complex Turbulent Flows, organized by the Institute for Computer Applications in Science and Engineering, NASA Langley Research Center, and the Air Force Office of Scientific Research. The symposium was held August 11-13, 1997 at the Radisson Hotel in Hampton, Virginia.

The symposium focused on complex turbulent flows, complexity being understood to indicate the presence of agencies which drive turbulence away from the Kolmogorov steady-state which underlies both elementary mixing length models and the simplest two-equation models. Sound modeling will remain the only practical way to compute such flows for the foreseeable future. The purposes of the symposium were:

– to evaluate recent progress in turbulence modeling
– to anticipate future modeling requirements
– to preview future directions for research.

The choice of particular topics for the symposium relied heavily on the outcome of the two Industry Roundtables co-sponsored by ICASE and LaRC. The symposium topics: compressible turbulence, curved and rotating flows, adverse pressure gradient flows, and nonequilibrium turbulence are all pacing issues in a wide range of industrial applications. For example, the turbulent flow over high-lift devices currently being investigated by Boeing and NASA, exhibits both strong adverse pressure gradients and substantial streamline curvature. Plans for a high-speed civil transport have brought renewed attention to compressible turbulent flows. Finally, aircraft maneuvering and control take place in a time-dependent, nonequilibrium turbulence environment. Lack of time ruled out consideration of the problem of predicting transition, which remains a difficult and crucial problem in aerodynamics. The range and complexity of the transition problem would demand a separate symposium to do it justice.

The editors would like to thank the participants for their contributions to the symposium and cooperation in making the symposium a success, and for their timely submission of the articles in this volume. The contribution of Ms. Emily Todd to organizing the symposium and the editorial assistance of Mrs. Shannon Verstynen are gratefully acknowledged.

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TABLE OF CONTENTS

Preface ix

Current and Future Needs in Turbulence Modeling
Jerry N. Hefner 1

Army Turbulence Modeling Needs
Thomas L. Doligalski 5

The Best Turbulence Models for Engineers
Peter Bradshaw 9

The Modeling of Turbulent Flows with Significant Curvature or Rotation
B.E Launder 29

A Perspective on Turbulence Modeling
Stephen B. Pope 53

Developments in Structure-based Turbulence Modeling
S.C. Kassinos and W.C. Reynolds 69

The Low Dimensional Approach to Turbulence
John L. Lumley and Peter Blossey 89

Modeling Non-equilibrium Turbulent Flows
Charles G. Speziale 107

Development of Algebraic Reynolds Stress Model for Non-equilibrium Turbulence
Sharath S. Girimaji 139

Toward a Vortex Method Simulation of Non-equilibrium Turbulent Flows
Peter S. Bernard 161

Two-point Closures and Statistical Equilibrium
Timothy T. Clark 183

Modeling the Turbulent Wall Flows Subjected to Strong Pressure Variations
K. Hanjalić, I. Hadžić, S. Jakirlić, and B. Basara 203

Some Structural Features of Pressure-driven Three-dimensional Turbulent Boundary Layers from Experiments
Roger L. Simpson, M. Semih Ölcmen, J.L. Fleming, and D.S. Ciochetto 223

Physics and Computations of Flows with Adverse Pressure Gradients
P.G. Huang 245

Computations of Complex Turbulent Flows Using the Commercial Code FLUENT
S.-E. Kim, D. Choudhury, and B. Patel 259

Simulation of Shock Wave-turbulent Boundary Layer Interactions Using the Reynolds-averaged Navier-Stokes Equations
Doyle D. Knight 277

Some Results Relevant to Statistical Closures for Compressible Turbulence
J.R. Ristorcelli 297

Transport Coefficients in Rotating Weakly Compressible Turbulence
Robert Rubinstein, Ye Zhou, and Gordon Erlebacher 329

Development of a Turbulence Model for Flows with Rotation and Curvature
S. Thangam, X. Wang, and Y. Zhou 349

Modeling and Analysis of Turbulent Flows in the Presence of Rotation and Curvature
X. Wang, S. Thangam, Y. Zhou, and A. Zigh 361

List of Attendees 373

CURRENT AND FUTURE NEEDS IN TURBULENCE MODELING

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The environment for conducting definitive turbulence modeling research has changed drastically over the past several years. With downsizing and reduced budgets in both industry and government, there is obviously reduced funding available for turbulence modeling research even though better turbulence modeling is still critical to computational fluid dynamics becoming more efficient, accurate, and useful. Within NASA, the funding reductions are compounded by the transition processes resulting from a restructuring and reorganization of the research and technology base program. The NASA R&T base program under the Aeronautics and Space Transportation Technology Enterprise is now outcome oriented and this is clearly evident from the goals of the Enterprise's Three Pillars for Success for Aviation and Space Transportation in the 21st Century. The Three Pillars' goals focus on three areas: global civil aviation, revolutionary technology leaps, and access to space. Under global civil aviation there are goals in aviation safety, environment (emissions and noise), and affordability (capacity and cost). Under revolutionary technology leaps, there are goals in barriers to high-speed travel, general aviation revitalization, and next-generation design tools and experimental aircraft. In the third area, there are goals aimed at reduced payload cost to low earth orbit. These goals are providing the framework and focus for NASA's Aeronautics and Space Transportation R&T program for the future; therefore, fundamental research to develop the needed turbulence modeling will have to be advocated and conducted in a manner to explicitly support these goals. There will be no single funding source for turbulence modeling research; instead, funding support will have to be derived from programs that are being developed to support the Three Pillar outcome goals. Turbulence modeling research of necessity will have to focus on providing tools for addressing issues such as advanced high lift systems, Reynolds number scaling, flow control, noise reduction, wind tunnel data corrections, and reduced design cycle time and costs, and these

M. D. Salas et al. (eds.), Modeling Complex Turbulent Flows, 1–3.

issues will undoubtedly fall under the purview of different Pillar goals. This will require improved coordination and cooperation across the turbulence modeling community and across the Pillar goals.

Where do we stand regarding turbulence modeling research? There have been much resources expended to date on turbulence modeling, and although much progress has been achieved, there are still no turbulence models that are being used consistently throughout industry to provide the accuracy and confidence levels necessary for routine computations of flows about complex aerodynamic configurations. Despite the projections throughout the early 1980's, computational fluid dynamics (CFD) has not replaced the wind tunnel. In fact, CFD, wind tunnel testing, and flight testing currently form the system which provides the aerodynamic data that industry uses to make design and production decisions regarding future aerospace vehicles. Thus, industry would be expected to need turbulence modeling and CFD to provide engineering information from models and algorithms that are accurate and reliable, that have known limits of applicability, that are user friendly, and that are cost-effective to use. Since turbulence modelers, in general, tend to work more closely with turbulence researchers and CFD algorithm developers, there is the tendency to push for as much physics as possible in their models and this may not be the best approach if the ultimate users of turbulence models want good engineering tools. The question then is: how much physics is enough? One way to address what the turbulence modeling customers need is to conduct turbulence modeling users workshops; these workshops would showcase the user community rather than the turbulence modelers. The desired outcome for these workshops would be to identify how industry, government, and academia are applying and using existing turbulence models, what are their needs, where are the successes, and what lessons have been learned. This hopefully would help identify where research needs to focus and how best to maximize the return on investment.

Turbulence modeling research to date suffers from problems other than knowing who the customer is. Much of the turbulence modeling research has focused on modeling the effect of turbulence on mean flows rather than modeling the turbulence physics; therefore, much of the turbulence modeling effort has focused on tweaking or adding constants and terms in the models to predict the available experimental data, which too often is mean flow data and not turbulence data. Although much has been said over the years regarding the need for definitive turbulence modeling experiments, there remains a paucity of high quality dynamic turbulence data useful for modeling and validation for flows about complex geometries. Another problem is that the numerics of the models may be inconsistent and not compatible with the CFD algorithm numerics; since the numerical algorithms for turbulence models place a greater demand on numerics than does the Navier-Stokes equations, both CFD'ers and turbulence modelers need to work together more closely. The bottom line is that to meet the engineering requirements of industry, research in turbulence modeling should be refocused to develop a hierarchy of turbulence models with increasing physics and known applicability and variability, and an increased emphasis must be placed on modeling and verification experiments on geometries and configurations representative of those of practical interest to aerospace designers.

To accomplish what needs to be done to successfully model, predict, and control the flows of interest to industry will require more cooperation and coordination among the turbulence modeling community. It will also require the turbulence modeling community to work within outcome goals like those being proposed by the Aeronautics and Space Transportation Enterprise. This will ensure that the turbulence modeling effort is focused on engineering tools useful to industry.

ARMY TURBULENCE MODELING NEEDS

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1. Introduction

Many Army systems involve turbulent flow. In order to accurately predict the performance of these systems it is necessary to account for the turbulent flow physics. While turbulence modeling techniques such as the Baldwin-Lomax and $k-\varepsilon$ models are adequate for many of these computations, many flows of contemporary Army interest involve non-equilibrium turbulence processes which are not accounted for in these conventional approaches.

2. Conventional Models

One example of such a flow occurs during dynamic stall, which occurs on oscillating helicopter rotorblades. Previous attempts (Dindar & Kaynak, 1992; Dindar *et al.*, 1993; Srinivasan *et al.*, 1993; Ekaterinaris & Menter, 1994; Srinivasan *et al.*, 1995) to assess the efficacy of a variety of turbulence models for the prediction of this flow have demonstrated relatively poor correlation with experimental data for even integrated quantities such as lift, drag and pitching moment (which are less sensitive to turbulence modeling details than local quantities such as wall shear stress). In a recent review article Carr and McCroskey (1992) concluded that: "Turbulence modeling becomes of crucial importance when dynamic stall is considered. This is particularly true when the question of incipient separation and dynamic-stall-vortex development is to be represented by a single turbulence model; under these conditions, the use of a turbulence model based on equilibrium attached boundary layers in steady flow (e.g. eddy viscosity, Baldwin-Lomax) is open to serious question. The task of predicting separation by definition deals with boundary layers that have experienced very strong pressure gradients, often both positive and negative; the flow approaching unsteady separation contains high levels of vorticity induced by these pres-

M. D. Salas et al. (eds.), Modeling Complex Turbulent Flows, 5–7.

sure gradients, and is strongly unsteady. Recent study has shown that modification of the turbulence model can completely change the resultant flow results; at the same time, very little has been experimentally documented about the character of turbulence under these conditions." Similar difficulties occur when attempting to compute the flowfield in the base region of Army missiles and projectiles. Previous studies (Childs & Caruso, 1987; Tucker & Shyy, 1993; Sahu, 1994; Chuang & Chieng, 1994) have met with varying degrees of success in predicting these flows; for example, a recent review by Dutton *et al.* (1995) stated that "all of the turbulence models employed failed to correctly predict the shear layer spreading rate, which is a fundamental characteristic of the near-wake flow."

3. Direct and Large Eddy Simulations

Recent developments in the formulation and application of direct numerical simulation (DNS) and large eddy simulation (LES) have raised the possibility for the use of these techniques for Army applications: in fact, Tourbier and Fasel (1994) have applied these approaches to the computation of supersonic axisymmetric baseflow, albeit at relatively low Reynolds numbers. While DNS and LES are clearly useful tools to understand flow physics, it seems unlikely that these approaches will be routinely used to design and analyze Army systems. Direct numerical simulation requires extremely large computational resources, especially at the high Reynolds numbers typically encountered. Large eddy simulation reduces these requirements to some extent; however, much more sophisticated subgrid scale models will be necessary in order to compute many flows of Army interest (this is a similar closure problem to that encountered when solving the Reynolds-averaged Navier-Stokes equations). Advocates for DNS and LES approaches often argue that as computer power continues to increase the use of these techniques will become more and more routine. While the enhanced power of these computers will undoubtedly allow the application of these methods to a larger number of aerodynamic flows, it seems unlikely to this observer that such application will be routinely performed in the industrial design setting: the current industrial trend is towards more multidisciplinary calculations, where aerodynamics is coupled with combustion, structural dynamics and other disciplines (and perhaps these aeromechanics disciplines are in turn coupled with a design optimizer, which itself runs for many iterations). The net effect of this multidisciplinary trend is to actually reduce the computational resources available for the aerodynamic aspects of the design problem being considered. The problem is further exacerbated by the move by many industries from large supercomputers towards heterogeneous computing environments formed by network workstations.