Contents

1 Introduction 1
1.1 Background . . . 1
1.2 Objectives . . . 2

2 RANS and LES 3
2.1 Introduction . . . 3
2.2 Reynolds-averaged Navier-Stokes equations . . . 3
2.3 Spalart-Allmaras one-equation model . . . 5
2.4 Shear Stress Transport model . . . 6
2.5 Unsteady RANS (URANS) . . . 7
2.6 Large-Eddy Simulation . . . 9

3 Detached Eddy Simulation 13
3.1 S-A DES . . . 13
3.2 SST-DES . . . 14
3.3 Aspects of the formulation . . . 15
3.4 Simulation design . . . 16
  3.4.1 DES grids . . . 16
  3.4.2 Unstructured grids and the definition of Δ . . . 18

4 DES Applications 21
4.1 Airfoil at high angle of attack . . . 21
4.2 Flow over a circular cylinder . . . 23
4.3 Flow over a sphere . . . 26
4.4 Separated flow around a forebody cross-section . . . 29
4.5 Simplified landing gear . . . 31
4.6 Delta wing . . . 36
4.7 Fighter aircraft . . . 37
  4.7.1 F-18C . . . 37
  4.7.2 F-15E . . . 39
4.8 Wall-layer modeling for LES . . . 42

5 Other Developments 45
5.1 Background . . . 45
5.2 Delayed Detached Eddy Simulation . . . 48
5.3 Test cases . . . 49
5.4 Zonal DES and Improved DDES . . . 53

6 Summary and Perspectives 55

Chapter 1

INTRODUCTION

1.1 Background

One of the most substantial challenges in Computational Fluid Dynamics (CFD) remains the accurate prediction of turbulent flows. Areas where accurate simulation strategies constitute a central element in analysis and design of engineering systems are diverse. These encompass a range of technologies in the defense, energy, and transportation industries, among many others.

The use of CFD as an integral part of engineering analysis and design continues to increase, in large part because of improvements across the broad spectrum that drives the wider application of computational science and engineering, e.g., more robust solution algorithms and the prominence of efficient computing platforms, especially low-cost commodity clusters. These and other factors supply much of the incentive for improving turbulence treatments in order to provide a meaningful level of accuracy for engineering applications that is commensurate with improvements in other areas.

Turbulent flows are currently modeled using a variety of simulation strategies. These range from correlations in simplified one-dimensional models to three-dimensional and time-dependent simulation techniques whose objectives include providing access to quantities that cannot be measured in experiments. The majority of predictions for engineering applications are obtained from solutions of the Reynolds-averaged Navier-Stokes (RANS) equations. The turbulence model in a RANS method is nominally responsible for the interaction between the unsteady, three-dimensional turbulent motions, which are not represented in the computation, and the motion of the mean flow which is computed. As discussed in these notes, these approaches are often acceptable in the thin shear layers where RANS methods have been calibrated. In other regimes, especially flows in which the turbulent eddies are not “standard”, i.e., not in the calibration range of the model, the performance of RANS models is, at best, uneven. This in turn motivates other strategies, one of the primary alternatives being Large-Eddy Simulation (LES).

Much of the continuing increase in the use of CFD in engineering is a result of the wider application of LES to prediction of turbulent flows in practical configurations. For most part, these applications are occurring in internal flows and especially to flows that include chemistry or contain more than one phase. Unfortunately, the computational cost which arises from the application of LES to a complete configuration such as an airplane, submarine, or road vehicle at practical Reynolds numbers is prohibitive and will remain so for the foreseeable future. The high computational cost of LES arises because of the resolution requirements for turbulent boundary layers, an issue that remains even with fully successful wall-layer modeling.

Hybrid methods have emerged as a popular approach for predicting complex flows. These methods combine RANS and LES techniques with the aim of capitalizing on the relative strengths of each approach. One of the most widespread RANS-LES methods in use today is Detached-Eddy Simulation (DES). DES was proposed by Spalart *et al.* [Spalart et al., 1997] as a cost-effective and plausibly accurate approach for predicting flows experiencing massive separation. The method was originally intended to predict the entire boundary layer using a RANS model and with an LES treatment intended for the separated regions. DES has performed well, enabling computationally feasible predictions of a range of high Reynolds number flows that are either difficult to model accurately using RANS models or impose a computational cost that prevents the application of LES. Given the successful applications of the technique to date, there continues to be relatively strong interest in expanding the range of applications which may be accurately predicted using DES.