Direct numerical simulation of a turbulent boundary layer separating over a curved wall using FastRK3

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Abstract: Flow separation, resulting from an adverse pressure gradient (APG), is encountered in many engineering applications, however, the physical mechanisms of separated turbulent boundary layers over curved walls are not yet well understood. The wall models employed in Reynolds-averaged Navier-Stokes (RANS) and large-eddy simulations (LES) of such flows are not predictive tools and need to be improved. In order to provide the necessary statistics for the validation of such models and explain the physical mechanisms of such flows, we have performed direct numerical simulations (DNS) of a spatially developing turbulent boundary layer over a curved wall with APG using our new projection-method called FastRK3. FastRK3 is a three-stage, third-order Runge-Kutta projection-method for the incompressible Navier-Stokes equations, which requires solving the Poisson equation for pressure only once per time step. In the current work, we employ FastRK3 to perform DNS of a spatially developing turbulent boundary layer separating over a curved ramp and study the dynamics of its turbulence kinetic energy.

Keywords: Pressure-correction method, explicit Runge-Kutta, fast Poisson solver, flow separation, turbulent flows, direct numerical simulation.

1 Introduction

Flow separation due to the adverse pressure gradient (APG) over curved bodies is accompanied by thickening of the boundary layer, a vortex filled wake and increased values of wall-normal component of velocity [1]. Reynolds averaged Navier-Stokes (RANS) wall-models fail when flow separation occurs [2]. There is a need to develop a deeper understanding of the physical mechanisms of separated turbulent flows to improve the RANS wall-models, which are often also employed in wall-modeled large-eddy simulations (WMLES) and hybrid RANS/LES methods. We have recently developed a new projection method, called FastRK3, to solve the incompressible Navier-Stokes (NS) equations in orthogonal curvilinear coordinates [3]. In the current paper, we present the results of DNS, employed by using FastRK3, of an incompressible turbulent boundary layer separating over a curved ramp.

2 Numerical method: FastRK3

FastRK3 is an explicit, three-stage, third-order Runge-Kutta based projection-method which requires solving the Poisson equation for pressure only once per time step versus three times by standard RK3 methods. In FastRK3, the NS equations in the orthogonal formulation are discretized in space on a staggered grid using the second-order central-difference scheme. FastRK3 has been verified, validated and produces nearly identical results to standard RK3 [3]. The absence of cross derivatives in the orthogonal formulation of NS equations results in a significant reduction in the number of terms to be computed and has also enabled us to develop and use in FastRK3 an FFT-based Poisson solver for pressure, called FastPoc. These properties make FastRK3 a faster method than those relying on three Poisson solvers per time step, e.g., standard RK3 methods, and/or using multigrid to solve the Poisson equation for pressure.

3 Results

We have applied FastRK3, to simulate the spatially developing turbulent boundary layer over the curved ramp experimentally studied by [4]. The turbulent inflow conditions were generated with the method of [5]. As in the experiments [4], the Reynolds number based on the momentum thickness at the inflow plane ($x = 0$, two ramp-lengths upstream of the ramp) was $\mathrm{Re}_{\theta_0} = 1100$. Figure 1 shows the contour plot of the mean turbulence kinetic energy, k. We present the DNS results of the mean flow in comparison with the experiments, and study the budget of k.

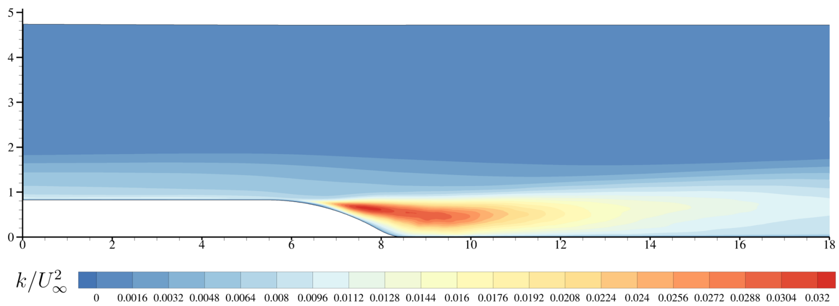

Figure 1: Contour of turbulence kinetic energy, k, for the flow over the curved ramp of [4].

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