Large eddy simulation of turbulent separated flow over a three-dimensional hill

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1 Introduction

The turbulent flow separation from a three-dimensional curved body is a complex problem which plays an important role in practical applications. In recent laboratory studies Simpson and co-workers [1, 2, 3] investigated extensively the separated flow over and around a 3D hill at high Reynolds number using LDV measurement techniques, oil flow visualisation and hot-wire anemometry. The examinations reveal the complex flow physics associated with the geometry of the hill. Complex separation occurs on the leeside and the evolving vortical structures merge into two large counter-rotating streamwise vortices downstream. There is also some evidence of low frequency spanwise meandering of the vortices in the wake.

The laboratory configuration mentioned above was simulated using LES. It consists of flow over and around an axisymmetric hill of height $H = 78$ mm and base-to-height ratio of 4; the approach-flow turbulent boundary-layer has a thickness of $\delta = 0.5H$. The Reynolds number of the flow based on the free-stream velocity $U_{ref} = 27.5$ m/s and the hill height H is $Re = 1.3 \cdot 10^5$.

2 Numerical model

The LES was performed with the Finite Volume Code LESOCC2 [4]. This solves the incompressible 3D time-dependent Navier-Stokes equations on body-fitted curvilinear block-structured grids using second order central differences for the discretisation of the convective and viscous fluxes. Time advancement is accomplished by an explicit, low-storage Runge-Kutta method.

The geometry of the computational domain is shown in Fig. 1. The size of the domain is $20H \times 3.2H \times 11.7H$ in streamwise, wall-normal and spanwise directions, respectively. The grid consists of $770 \times 240 \times 728$ cells in these

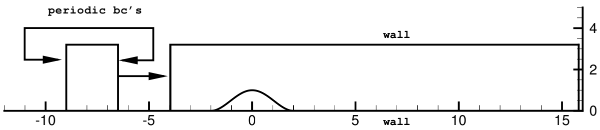

Fig. 1. Sketch of the computational domain and inflow generator.

directions. The inflow conditions are obtained by performing simultaneously a separate periodic LES of channel flow in which the mean velocity is forced to assume the experimental vertical distribution using a body-force technique [5]. The length of the channel is $1.8H = 3.6\delta$ and the number of cells in streamwise direction is 110. The cost of the precursor simulation is, therefore, 1/8 of the total cost. A no-slip condition is employed at the bottom wall while the Werner-Wengle wall function is used at the top wall, so that the boundary layer there is not well resolved. Free-slip conditions are used at the lateral boundaries and convective conditions at the exit boundary. The quality of the grid resolution is judged by determining the cell size in wall units. The centre of the wall-adjacent cell is located at $y_1^+ \sim 2$. The streamwise and spanwise cell sizes in wall units are roughly 70 and 30, respectively. These values are just within the limits of the recommendations given by Piomelli & Chasnov [6] for wall resolving LES. As for the quality of the inflow conditions, the mean streamwise velocity, turbulent kinetic energy and shear-stress profiles (not shown here) are in good agreement with experimental data.

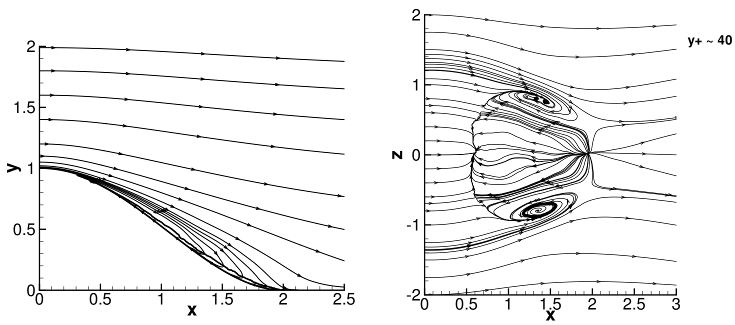

Fig. 2. Left, streamlines in midplane. Right, streamlines at $y^+ = 40$.

3 Results

An illustration of the mean flow obtained in the simulation is displayed in Fig. 2 by showing streamlines of the flow in the symmetry plane (left) and in a plane close to the hill wall at $y^+ \sim 40$(right) With respect to the experiments, the thickness of the recirculation zone is well predicted although the separation occurs somewhat earlier in the simulation. The flow topology is also rather well predicted with the two counter-rotating vortices appearing roughly at the same location as in the experiment.

A visualization of the instantaneous coherent structures of the flow is displayed in Fig. 3. It shows an iso-surface of pressure fluctuations; the color represents the y-coordinate. In animations of the flow, coherent structures are observed to form in the lee of the hill and are convected downstream. Many of them have the shape of a hairpin vortex although due to the high level of turbulence they are usually rapidly deformed. It happens frequently that structures appear only in one side of the wake. In the instant observed in the picture all the structures are in the left part of the wake, while no activity is observed in the right part. There are also instants in which structures appear everywhere in the wake. Time signals of velocity recorded in the near wake show pronounced peaks when one of these big structures crosses the recording point.

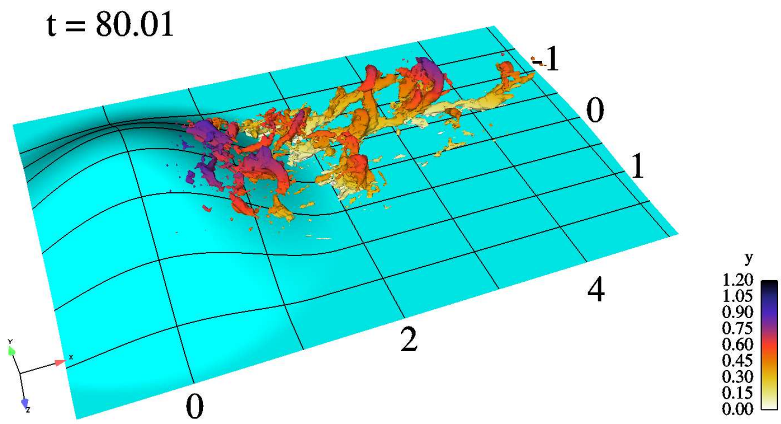

Fig. 3. Iso-surface of pressure fluctuations.

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