LES WITH DOWNSTREAM RANS FOR FLOW OVER PERIODIC HILLS AND A MODEL COMBUSTOR FLOW

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Abstract A simple coupling method between an LES and a downstream RANS simulation is presented which avoids the definition of a complex interface. The technique is scrutinized for two canonical flows: separated flow inside a channel with periodic contractions and a co-annular swirling jet with sudden expansion. The hybrid simulations are evaluated by comparison with LES results of the complete flow field on the same and finer grids as well as experimental data in the case of the swirl flow.

INTRODUCTION

The combination of flow separation, hydrodynamic instabilities, turbulence, and the formation of large coherent structures occurs in many fluid flow applications of engineering interest. These complex flow physics are difficult to model by Reynolds-Averaged Navier–Stokes (RANS) simulations, even when conducted in unsteady manner (URANS). Large eddy simulation (LES) is better suited for this purpose as the large-scale motion is computed directly and only the small-scale motion modelled. Full LES, however, is often not affordable for very complex high-Reynolds number flows and/or extensive parameter studies which both are frequently required in engineering applications. A remedy is zonal hybrid RANS/LES coupling. This method employs the more expensive LES only in flow regions where RANS predictions are likely to be inadequate, e.g., in regions where large coherent structures are formed. A special case of this technique is LES with a downstream RANS zone considered here. It is of practical interest in particular for swirl flows where the radial pressure distribution is critical far downstream of the region of primary interest [1]. As a consequence, a simple outflow condition cannot be applied close to this region and a lengthening of the domain by adding a URANS zone may be an attractive alternative to more complex boundary conditions.

METHODOLOGY

For all cases presented here, LES using the Smagorinsky model ($C_s = 0.1$) is applied in the flow region under investigation. Downstream of a specified location a RANS simulation using the Spalart and Allmaras (SA) model [2] is performed on a coarser grid, which can be two-dimensional for 2D geometries. In that case, transition between the LES and RANS zones is accomplished by a zone of URANS on a 3D grid. At the matching location of the LES and URANS zones, the subgrid-scale eddy viscosity of the LES is replaced by the eddy viscosity from the transport equation in the SA model. The latter is, in fact, solved in the entire computational domain, but only in the URANS and RANS zones the resulting viscosity is used in the momentum equations. This approach, although based on pre-defined locations, avoids the specification of an explicit coupling interface with local averaging and enrichment [3] and, hence, is substantially easier to implement. It also avoids the issue of specifying boundary conditions for the RANS model at the matching locations.

The simulations were carried out with the Finite Volume Code LESOCC2 (LES On Curvilinear Coordinates) [4] developed at the Institute for Hydromechanics at the University of Karlsruhe. It solves the incompressible time-dependent filtered Navier–Stokes equations together with any number of transport equations required for the turbulence models on body-fitted curvilinear block-structured grids. Second-order central differences were used for the discretization of the convection and diffusion fluxes. Only for the convection term in the transport equation for the eddy viscosity the monotonic HLPA scheme was employed. An explicit, low-storage Runge–Kutta method is used for time advancement.

FLOW OVER PERIODIC HILLS

This configuration was devised by Mellen et al. [5] and detailed reference data are presented in [6]. The Reynolds number formed with the hill height h and the bulk velocity over the crest is $Re_b = 10,595$. The current simulation is divided into three distinct zones (Fig. 1). The first zone is computed with LES using wall functions and periodic boundary conditions in the downstream direction. $200 \times 64 \times 92$ interior cells are used in the downstream, wall-normal and lateral directions, respectively. This zone provides the inflow data for the second zone. For the second zone, also LES is performed using the same resolution as in Zone 1, however, before the crest of the next hill is reached, the simulation switches from LES to URANS, i.e., the third zone begins. Within the third zone the grid becomes two-dimensional resulting in a 2D RANS simulation. At the outflow, Neumann boundary conditions are applied.

Typical results for the average flow are shown in Fig. 1. The streamlines reveal that, for the 2D RANS solution, reattachment occurs far too late, consistent with RANS results in the literature. On the other hand, the LES in Zone 2 delivers results similar to the reference solution of Zone 1, albeit with a slightly longer recirculation region. Both reattachment lengths of $4.1\,h$ and $4.3\,h$ for Zone 1 and 2, respectively, are close to the reference value of 4.6 to $4.7\,h$ in [6].

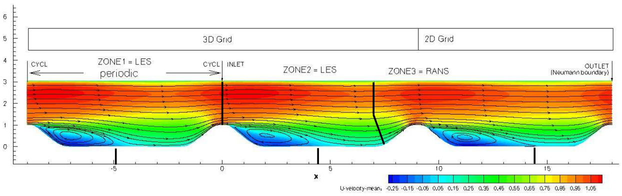

Figure 1: Setup of simulation and mean downstream velocity contours and streamlines of the spanwise averaged flow field for the flow over periodic hills (vertical tick marks indicate reattachment locations).

MODEL COMBUSTOR FLOW

In many combustion devices, a swirling flow is used to stabilize the flame through a recirculation zone. One such flow (see Fig. 2) was investigated experimentally by Sommerfeld et al. [7], where in addition to the outer (annular) jet with swirl, a second jet without swirl is introduced at the axis of symmetry. The Reynolds number based on the bulk velocity of the outer jet U_b and the diameter of the outer jet D is $Re_D = 65,380$; the swirl number is $S \approx 0.45$.

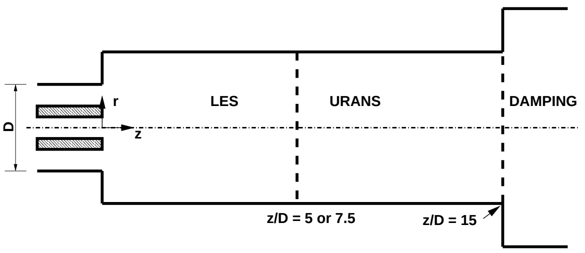

Figure 2: Schematic of the model combustor (not to scale).

Two hybrid RANS/LES were performed with approximately $670,000$ cells and the URANS region starting at either $z = 5.0$ or $z = 7.5$ (no 2D RANS zone was used). In addition, two full LES were carried out, one on the same computational grid and the other on a finer grid using roughly 2.9×10^6 cells. Long time-averages were required and, for the data presented here, exceeded $110D/U_b$. A damping zone was employed at the outflow of all simulations.

Fig. 3 shows profiles of average axial velocity at two axial stations. For reference, the experimental values are included as well. The agreement with the experimental data is good for all methods. The two hybrid RANS/LES yield results similar to the coarse grid full LES.

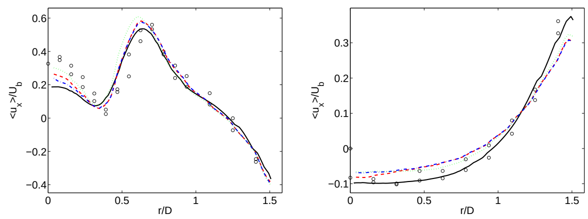

Figure 3: Average axial velocity over radial distance in the model combustor at $z/D = 0.812$ (left) and $z/D = 2.422$ (right); (○) experiments, (—) fine-grid LES, (– –) coarse-grid LES, (– · –) LES with RANS at $z \geq 5.0$, (· · ·) LES with RANS at $z \geq 7.5$.

The potential savings in terms of grid points are modest with the two configurations considered here for testing purposes, but they can be substantial in other applications. At the colloquium, detailed comparisons of the results with the reference data will be reported.

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