Progress in the large-eddy simulation of an asymmetric plane diffuser

By Massimiliano Fatica & Rajat Mittal[1]

1. Motivation and objectives

The flow through a plane asymmetric diffuser is a good test case for assessing the capability of LES since it contains features such as large scale unsteady separation and strong intermittency which are difficult to capture using conventional modeling approaches. Previous attempts to simulate this flow (Kaltenbach, 1994) have significantly underpredicted the extent of separation.

The objective of the present research is to understand why the previous simulations did not predict the flow separation correctly. This study focuses on mesh refinement and matching of the inlet velocity profile. In order to perform this study, the flow solver of Kaltenbach (1994) was modified to increase its accuracy and efficiency. The improved algorithm allows for better resolution at affordable CPU cost. The present results are compared with those of Kaltenbach (1994) and the experimental data of Obi *et al.* (1993).

2. Accomplishments

2.1 Numerical method

Although previous simulations used a fully implicit method (Kaltenbach 1994, Choi *et al.* 1992), the time-step in this flow is limited mainly by the turbulence time-scale in the inlet and not by numerical stability considerations. This fact implies that much of the potential benefit of using the implicit scheme is not fully realized in this case. In the current study, the semi-implicit solver used for the simulations of flow past the circular cylinder (see Mittal, this volume) has been been modified for solving flow through the diffuser. The direct inversion of the momentum equations coupled with the fast iterative pressure Poisson solver results in an extremely efficient algorithm. The Fourier discretization method provides better spanwise resolution, and it was found to be a cost effective alternative to increasing the number of grid points. The spanwise velocity is collocated at the pressure node, and dealiasing is performed using the $(2/3)^{rd}$ rule in order to guarantee kinetic energy conservation. The increased efficiency allows us to use a finer mesh and to accumulate statistics over a longer period than has been possible before.

2.2 LES of flow in an asymmetric planar diffuser

The flow configuration consists of a asymmetric planar diffuser with a 10^o angle and expansion ratio of 4.7. The turbulent inflow corresponds to a fully developed

1 Present address: University of Florida, Dept. of Mechanical Engr., Gainesville, FL

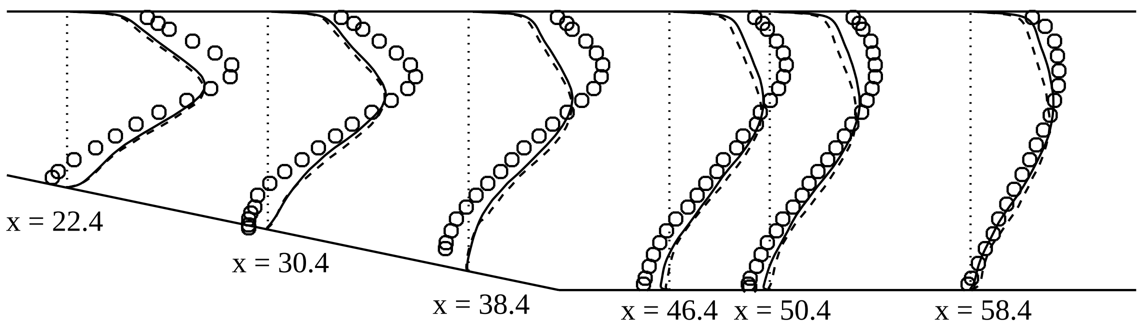

FIGURE 1. Mean velocity profiles $x + 10U/U_b$ in the exit section of the diffuser. Effect of spanwise resolution. ——— Run A ; ---- Kaltenbach (1994); ∘ Experimental data by Obi *et al.* (1993).

channel flow with a bulk Reynolds number $Re_b = 9000$. The bulk Reynolds number is defined as $Re_b = hU_b/\nu$ where h, U_b, and ν are the inlet half-channel height, inlet bulk velocity, and kinematic viscosity, respectively. The spanwise domain size is $4h$.

The disparity in the length and time-scales in the inlet and exit sections of the diffuser imposes significant demands on the computational resources. The sensitivity of the flow to inflow/outflow conditions also causes difficulties for experimental measurements, and a parallel experimental effort is currently underway (Buice & Eaton, 1995) to provide reliable data for validation purposes.

Previous LES studies (Kaltenbach, 1994) have under-predicted the extent of separation, and our objective is to investigate the reason for this discrepancy. Possible causes include mismatch of upstream and/or downstream conditions, low streamwise/spanwise resolution, and small spanwise domain size.

2.3 Results

To investigate the effect of spanwise resolution, one simulation of this flow has been carried out on the same $163 \times 65 \times 64$ (streamwise $\times$ vertical $\times$ spanwise) grid that was used by Kaltenbach (1994), but with the better resolution in the spanwise direction provided by the spectral discretization (this simulation will be hereafter referred as Run A).

Kaltenbach realized that the simulation was under-resolved on this mesh, but could not afford better resolution with his less efficient, fully implicit code. He could afford better resolution in the separate channel flow simulation used to produce the inflow data, however, and consequently he used 128 points in the span for this purpose. The increased accuracy associated with the 128 points for the inflow generation can not be sustained on the 64 point diffuser mesh, and thus the solution is assumed to degrade with increasing distance downstream from the inlet. Inflow data for our run A was generated with Fourier collocation in the spanwise direction using 64 points. The statistics from this simulation were found to be nearly identical to Kaltenbach's full finite difference calculation done on 128 points. The main

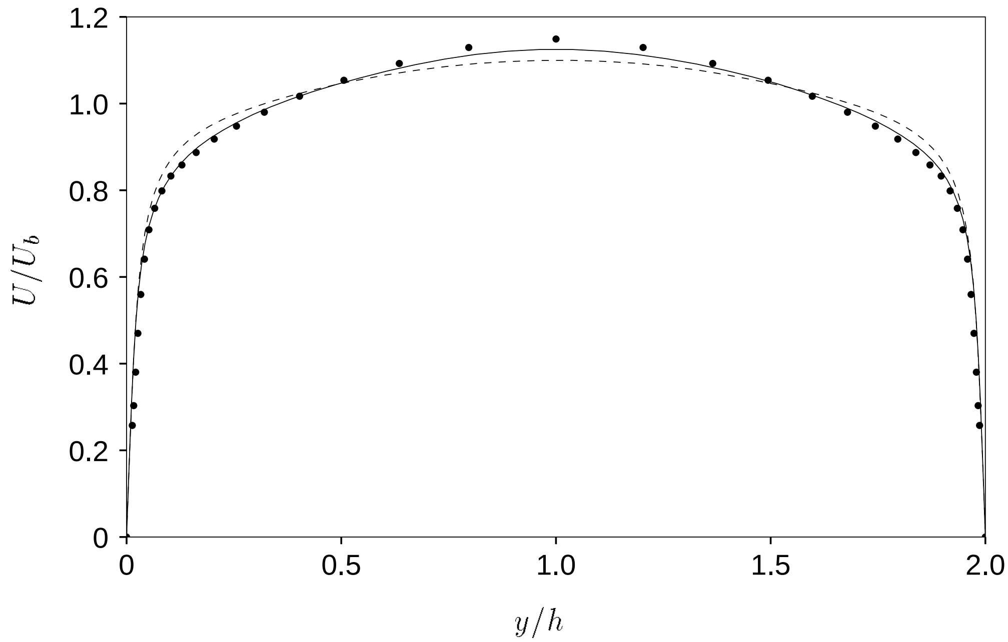

FIGURE 2. Comparison of inflow profiles with experiments: ---- Inlet condition for Run A ($\Delta x^+_{in} = 100$) ; ——— Inlet condition for Run B ($\Delta x^+_{in} = 50$) ; • Experimental data by Buice & Eaton (1996).

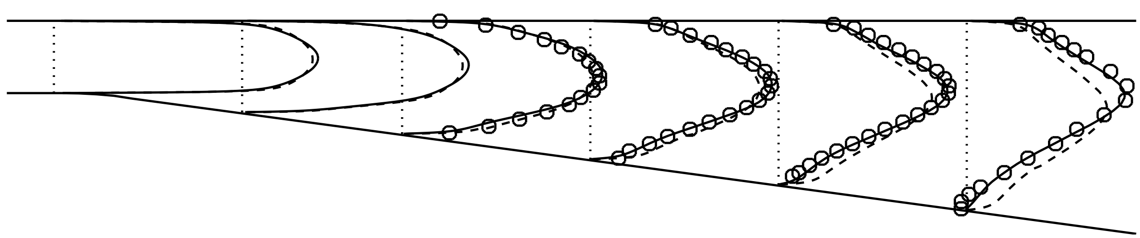

FIGURE 3. Mean velocity profiles $x + 5U/U_b$ in the inlet section of the diffuser. Effect of streamwise resolution. ——— Run B ; ---- Kaltenbach (1994); ○ Experimental data by Obi *et al.* (1993).

difference is that Fourier collocation was also used in the diffuser simulation, which means the quality of the inflow data should be preserved throughout the domain.

The statistics from Run A have been accumulated over a period of about $1200 U_b/h$, which corresponds to about 50 exit inertial times scales. Mean streamwise velocity profiles in the downstream section of the diffuser are shown in Fig. 1. The results of Run A are nearly identical to those of Kaltenbach at the first station in Fig. 1.

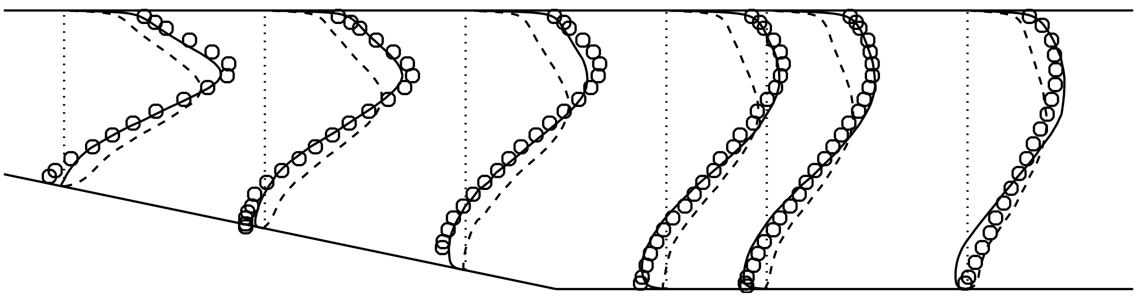

FIGURE 4. Mean velocity profiles $x + 10U/U_b$ in the exit section of the diffuser. Effect of streamwise resolution. ——— Run B ; - - - - Kaltenbach (1994); ∘ Experimental data by Obi *et al.* (1993).

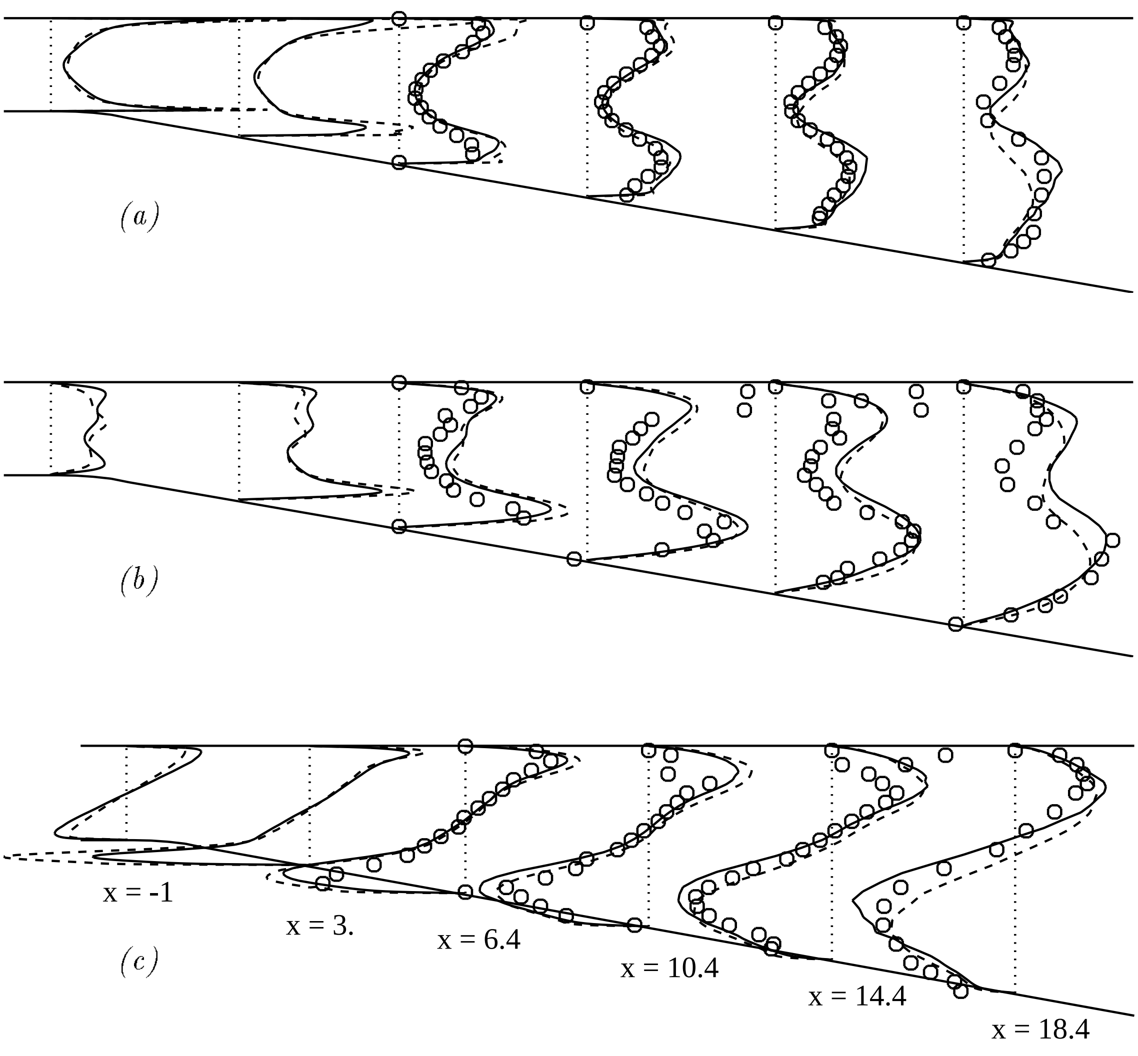

FIGURE 5. Variances $x + 150\overline{uu}/U_b^2$ *(a)*, $x + 500\overline{vv}/U_b^2$ *(b)* and shear stress $x + 750\overline{uv}/U_b^2$ *(c)* in the first half of diffuser. ——— Run B - - - - Kaltenbach (1994); ∘ Obi *et al.* (1993).

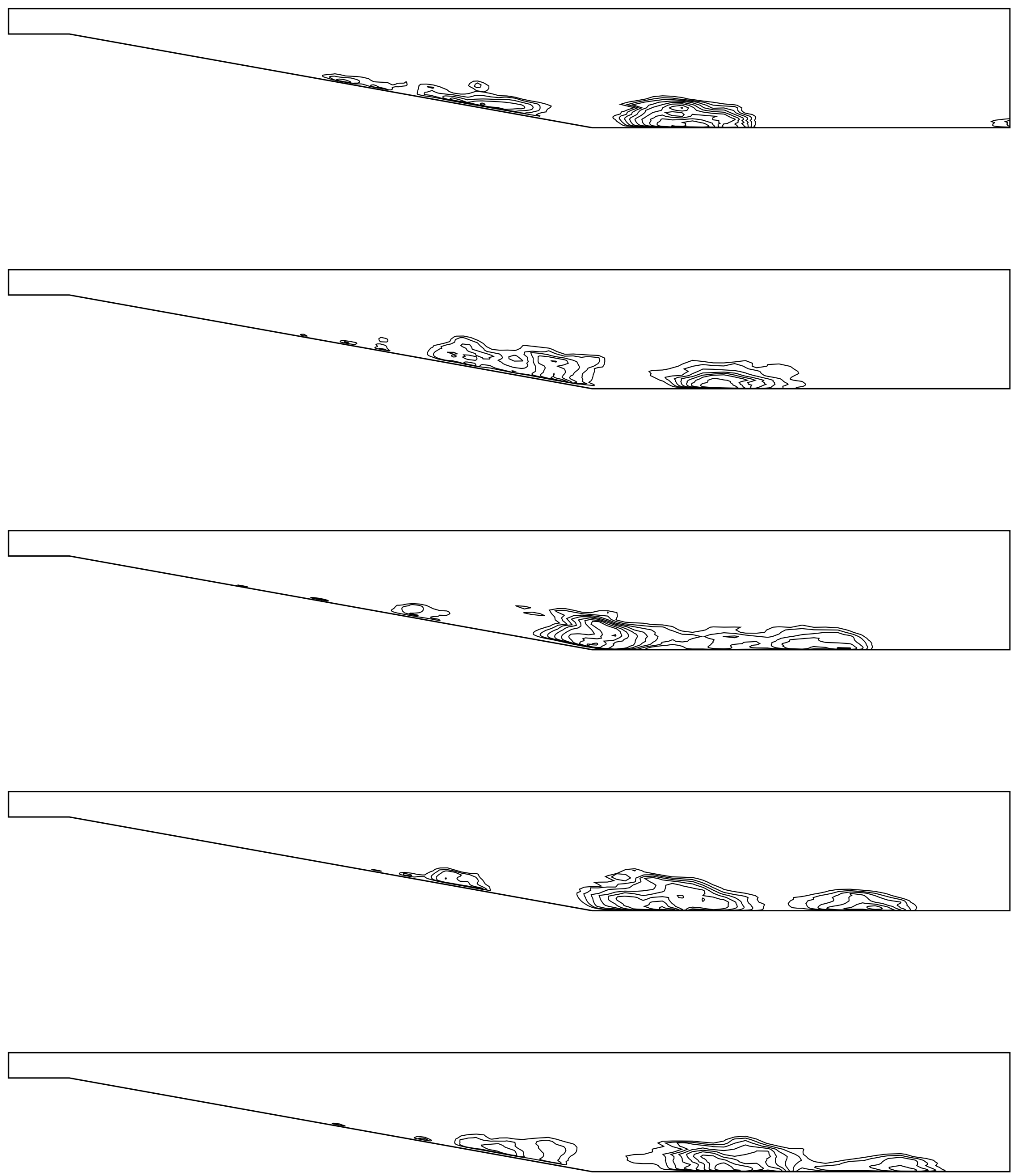

FIGURE 6. Contour line of negative streamwise velocity averaged in the spanwise direction. Time increment among frames is approximately $30U_b/h$.

Small differences can been observed over the next three stations with Run A producing a slightly larger separated region. Overall the differences are slight, however, and Run A is still in considerable disagreement with the experimental data.

The current mismatch with the experimental data appears to be related to the streamwise resolution. Both Kaltenbach's and the Run A simulation are underresolved in the streamwise direction which results in mean velocity profiles upstream of the diffuser that are noticeably fuller near the wall as compared with the experimental data. As shown in Fig. 2, doubling the number of streamwise mesh points in the inflow generation ($\Delta x^+_{in} = 50$ compared to the previous $\Delta x^+_{in} = 100$) has shown to lead to profiles that agree well with the experimental data.

A new simulation with improved streamwise resolution has been started. This simulation, referred to as Run B, has a streamwise mesh spacing of $\Delta x^+_{in} = 50$ at the inlet and contains $273 \times 65 \times 64$ points. Although the statistics have not yet converged, some preliminary results will be presented below. Due the disparity in the time-scales in the inlet and outlet section, the statistics converge more slowly in the outlet section. Thus the results near the inlet are probably trustworthy while those near the outlet may change as the simulation is run further in time. The figures shown are obtained using statistics accumulated over a period of about 400 inlet inertial time scales (U_b/h). Measured in terms of exit inertial time scales, however, the averaging time is only about 18 units.

It can now be observed in Figs. 3 and 4 that there is good agreement between the LES computation and the experimental data in all the stations except the last one. This can be an effect of insufficient average time. In Fig. 5 velocity fluctuations are plotted in the first half of the diffuser. Also, for these quantities, better agreement with the experiment is found.

Using LES, not only statistical quantities can be obtained, but also instantaneous information. We are interested in understanding the dynamics of the separation: that there is in this flow a very unsteady and intermittent process as can be noticed from Fig. 6. A computer animation is being generated to visualize the process.

3. Future plans

From the result of the fine simulation (Run B), it seems pretty clear that the previous disagreement between LES and experiments was due to inadequate streamwise resolution. The current simulation will be continued until the statistics are fully converged. A detailed comparison of the results will be made with both the data of Obi *et al.* (1993) and that of Buice and Eaton (1996).

Acknowledgment

The fine simulation has been performed on the Aeronautical Systems Center Cray C90 under the ASC MSRC Pioneer Program.

REFERENCES

Buice, C. U. & Eaton, J. K. 1995 Experimental Investigation of Flow Through an Asymmetric Plane Diffuser. *Annual Research Briefs.* Center for Turbulence Research, NASA Ames/Stanford Univ., 117-121.

Choi, H., Moin, P. & Kim, J. 1992 Turbulent drag reduction: studies of feedback control and flow over riblets. *Report No. TF-55,* Thermosciences Div., Dept. of Mech. Engr., Stanford Univ.

Kaltenbach, H-J. 1994 Large-eddy simulation of flow through a plane, symmetric diffuser. *Annual Research Briefs.* Center for Turbulence Research, NASA Ames/Stanford Univ., 175-184.

Obi, S., Aoki, K. & Masuda, S. 1993 Experimental and computational study of turbulent separating flow in an asymmetric plane diffuser. *Ninth Symposium on Turbulent Shear Flows,* Kyoto, Japan, 305.