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Laminar and turbulent channel flow simulations and the choice of appropriate boundary conditions

Transitional flow over a backward-facing step is studied by large eddy simulation (LES) and direct numerical simulation (DNS). The simulation was performed at a Reynolds number of 3000 *based on step height and inlet stream velocity. We compare the passive flow and the flow controlled by a twodimensional acoustic manipulation in front of the separation line. The aim of the boundary layer control is to decrease the reattachment lenght.*
Huppertz & Janke (1995/1997) demonstrated experimentally a reduction of the reattachment lenght of approximately 30% for a certain frequency of the acoustic disturbancies. Our statistical results show a good agreement with the experimental data of Huppertz & Janke.
The problem of the choice of suitable outflow boundary conditions was considered with respect to the reduction of the lenght of the computational domain and the reduction of computaional expenses respectively.

1. Mathematical model and fluid physical task

The governing equations are the Navier-Stokes equations for an incompressible fluid.

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot \vec{u}\vec{u} = -\nabla p + \nabla \cdot \nu \nabla \vec{u} \qquad \text{and} \qquad \nabla \cdot \vec{u} = 0 \tag{1}$$

in the flow region $\Omega \subset R^3$. At the time $t = t_0$ the initial value

$$\vec{u}(x, t_0) = \vec{u}_0(x) \qquad \text{on} \qquad \Omega \tag{2}$$

is given. $\vec{u} = (u, v, w)$ and p stand for the velocity field and the modified pressure (pressure over density), ν is the kinematic viscosity. In the case of LES $\vec{u}$ stands for the coarse grid part of the velocity and ν includes the small grid part of the velocity described by a subgrid-scale model. Besides the LES model of Smagorinskij the dynamic subgrid-scale model of Germano is used following the procedure proposed by Akselvoll & Moin (1995).
On the Dirichlet boundary $\Gamma = \Gamma_{in} \cup \Gamma_m$ the solution must fulfil the inflow and no-slip boundary conditions $u = u_{inflow}, \quad v = w = 0, \, on \, \Gamma_{in}$. At the upper boundary of the computational domain a no-stress wall is assumed. Suitable outflow boundary conditions shortly summarized as

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial w}{\partial x} = 0, \qquad \text{on} \qquad \Gamma_{out} \,, \tag{3}$$

$$\nu\frac{\partial u}{\partial x} = p, \quad \nu\frac{\partial v}{\partial x} = \nu\frac{\partial w}{\partial x} = 0, \qquad \text{on} \qquad \Gamma_{out} \,, \tag{4}$$

which are used alternatively. The velocity components u, v and w correspond to the streamwise (x), spanwise (y) and the vertical (z) direction, respectively. The pde system (1)–(4) describes the nonsteady three dimensional flow. By an evaluation of the instantanous velocity and pressure fields during our time integration we have produced the time averaged fields (mean value and rms statistics - up to second order statistics) as a basis for comparisons with experimental data which are only given as time averaged data.
Evaluating the differential equations on quadrilateral finite volumes we get a second order accurate scheme. We use four staggered grids for the discretization of the three components of the momentum equation and the continuity equation, i.e. the pressure is defined at the centre of the cell und the velocity components on the cell sufaces. Doing this we get a conservative finite volume scheme, even for the kinetic energy balance.
The time discretization of the governing equations is achieved using a semi-implicit technique following Chorin (1968) and Hirt/Cook (1972). For the evaluation of velocity fields $\vec{u}$ with $\nabla \cdot \vec{u}$ an iterative solver was used.
The described features were implementet in the code MLET (Werner, 1991) for vector computers. The solution method was adapted and improved for parallel architectures and then implemented on the massively parallel system Cray T3D (Bärwolff & Schwandt, 1995). Some detailed results of LES and DNS computations with the code MLET are presented in [1] and [2].

2. Results

Figure 1 shows the computational domain of our numerical simulation. The comparisons of the effect of the boundary conditions (3) and (4) show the strong dependencies of the upstream reflection on the choosen length of the computational domain. The wall shear stress graphs (u_τ) in the figures 3 and 4 show for the natural boundary condition a smaller upstream effect to the position of the reattachment lenght X_r using different channel lengths than in the case of (3). $L = L_x - L_s$ denotes the lenght of the computational domain behind the step.

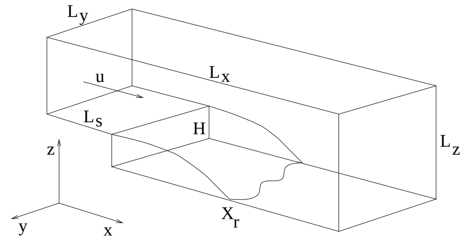

Figure 1: backward facing step configuration

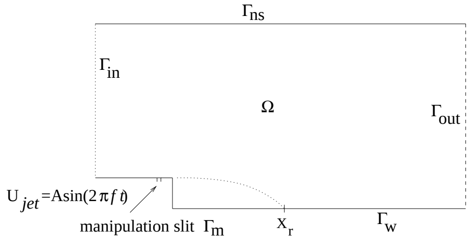

Figure 2: bfs channel cut

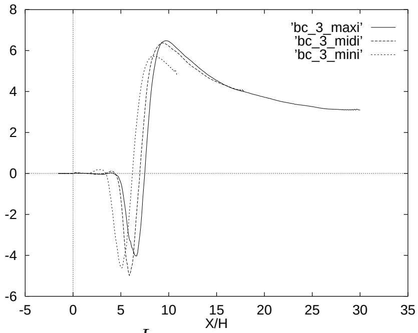

Figure 3: u_τ for $\frac{L}{H} = 11, 17, 28$ with the bc (3)

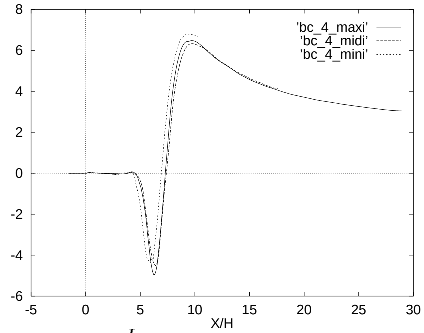

Figure 4: u_τ for $\frac{L}{H} = 11, 17, 28$ with the bc (4)

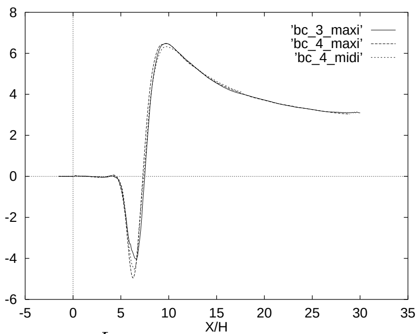

Figure 5: u_τ for $\frac{L}{H} = 11, 17, 28$ with the bc (3) and (4)

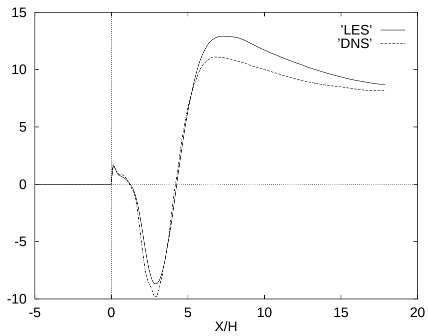

Figure 6: u_τ, DNS and LES, $A = 0.01 u_{inflow}$

Figure 5 shows that the differences of the position of X_r can by neglected if the channel length L is at least equal to $17H$. Hence we use for our LES-production runs the channel lenght $L = 17H$. In view of the experiences with the boundary condition (4) presented in figure 4 we do some further investigations with boundary conditions of natural type with the aim to decrease the necessary length of the computaional domain. The computational amount to realize the boundary condition (4) is the same as in the case of the standard condition (3).

3. References

1 Bärwolff, G.: DNS and LES einer transitionellen Strömung über eine rückwärts gewandte Stufe mit und ohne Grenzschichtmanipulation; TU Berlin, FB Mathematik, Preprint Nr. 548, März 1997.

2 Bärwolff, G., Wengle, H., Jeggle, H.: DNS of Transitional bfs Flow Manipulated by Oszillating Blowing/Suction; H.W. Rodi (ed.): Proc. of the 3rd Int. Symp. on Eng. Turbulence Modelling and Measurements, May 27-29, 1996, Crete, Greece, Elsivier Science, Amsterdam 1996.

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