DNS and LES of a backward facing step (bfs) flow with an upstream boundary layer control

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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 copare 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 good agreement of the LES results with the experimental data and the DNS results allows us to use the large eddy simulation as an inexpensive method to perform parameter studies of the backward facing step flow which are impossible with a direct numerical simulation.

0. Motivation

In a series of experiments concerning the separated flow over a backward facing step (bfs), Huppertz & Janke (1995/97) studied the influence of an acoustic control of the boundary layer on the reattachment length. They observed a reduction of this parameter depending on the frequency and the acoustic pressure of the control signal.
In principle the transitional character of the bfs flow - laminar before the separation and a turbulent shear layer in the wake region - and the moderate Reynolds number of the experiments ($Re = 3000$) would allow to perform direct numerical simulations simultaneously with the experiments. However, the inevitable amount of computing time and memory capacity which is required for a direct numerical simulation makes this tool much too expensive for extensive parameter studies with the aim to explain boundary control effects on the bfs flow. The DNS for a single parameter constellation needs days, weeks or even months and wide parameter variations would need months or years.
The large eddy simulation is known as a cheaper instrument for turbulent flow simulation than the direct simulation. We present here results indicating that LES is a suitable instrument for qualitative and quantitative parameter studies in the boundary layer control of a bfs flow.
For the validation of the LES results we refer to the above mentioned experimental data (Huppertz & Janke, 1995/1997) and to the results of a DNS (Bärwolff, Wengle & Jeggle, 1996).

1. Mathematical model and numerical solution method

Model equations and boundary conditions

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

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot \vec{u}\vec{u} = -\nabla p + \nabla \cdot \nu \nabla \vec{u} \qquad (1)$$

$$\nabla \cdot \vec{u} = 0. \qquad (2)$$

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

$$\vec{u}(x, t_0) = \vec{u}_0(x) \qquad (3)$$

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

$$u = u_{inflow}, \quad v = w = 0, \; on \; \Gamma_{in}. \qquad (4)$$

At the upper boundary of the computational domain a no-stress wall is assumed. The boundary condition reads

$$w = 0, \qquad \frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0, \; on \; \Gamma_{ns}. \qquad (5)$$

Suitable outflow boundary conditions shortly summarized as

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial w}{\partial x} = 0, \; on \; \Gamma_{out}, \qquad (6)$$

$$\nu \frac{\partial u}{\partial x} = p, \quad \nu \frac{\partial v}{\partial x} = \nu \frac{\partial w}{\partial x} = 0, \; on \; \Gamma_{out}, \qquad (7)$$

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)–(7) 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.

Numerical solution method

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).

The computational domain

Figure 1 shows the computational domain of our numerical simulation.

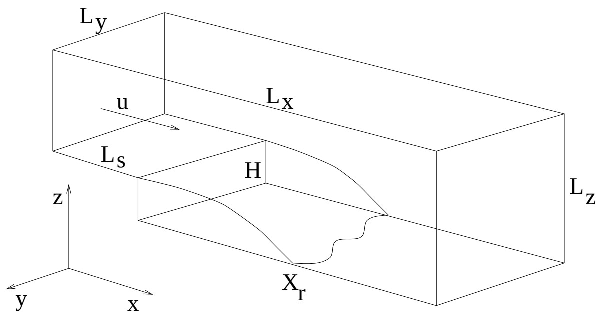

Figure 1: backward facing step configuration

For the streamwise length L_x, the spanwise width L_y and the vertical height L_z we set $(L_x, L_y, L_z) = (22H, 6H, 12H)$. The choice of the vertical height is based on experiences concerning the dependency of the reattachment lenght on L_z. Only beyond $11H$ the dependency of the reattachment lenght can by neglected. The inlet section or the step has the length $L_s = 5H$. The inflow profile was assumed as a block profile with the velocity $u_{inflow} = const.$. Non-uniform grid spacings for the streamwise and vertical directions are used. In the x- and the z-directions we consider a refined grid around the step. In z-direction fine spacings are used near the lower. In the spanewise direction uniform grid spacings are used.
Some preparing computations showed the development of the block profile to the Blasius profile near the separation line measured by Huppertz & Janke (1997). The step-height Reynolds number is defined as $Re = u_\infty H/\nu$.
For the LES a total of 256 grid cells is used in the x-direction and of 64 cells in the y-direction. The number of cells in the vertical direction is 80, of which 40 are placed within the step ($z < H$). For the reference DNS we refined our grid in all directions to half the stepsize.

2. Fluid physical task

Figure 2 shows a symmetry cut through the channel with the position of the step and the manipulation slit. In the case of the control of the upstream boundary layer the acoustic manipulation means a blowing and suction with a certain frequency. With this mechanism no additional mass flux is inserted into the channel by the control in a time averaged sense. Thus we have a boundary condition of the form

$$u = w = u_{jet} \quad on\ \Gamma_m\ , \tag{8}$$

which realizes a jet with an angle of $\pi/4$.

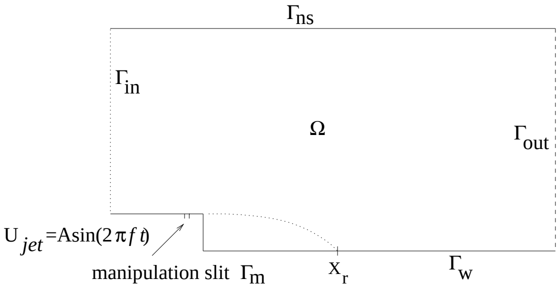

Figure 2: bfs channel cut

Because of the absence of detailed information about the blowing and suction during the acoustic control it was simulated by a sine function $u_{jet} = A\ sin(2\pi\, ft)$ and calculations for $A = 0.1\, u_{inflow}$, $A = 0.01\, u_{inflow}$ and $A = 0.001\, u_{inflow}$ were done.
With increasing of the amplitude A a decrease of the recirculation length was observed both in the experiment and in the simulation.
In the spanwise direction periodic boundary conditions are assumed. The time steps of the numerical integration method are choosen in such a way that i) the stability restrictions are fulfilled and ii) the control period - one blowing/suction cycle - is resolved by 20 time steps.

3. Some remarks to the choice of outflow boundary conditions for the velocity field

The comparisons of the effect of the boundary conditions (6) and (7) 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 (6).
$L = L_x - L_s$ denotes the lenght of the computational domain behind the step.

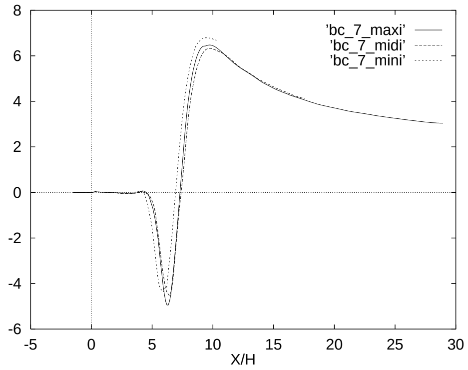

Figure 3: u_τ comparison for $L = 11H$, $17H$, $28H$ with the natural bc (7)

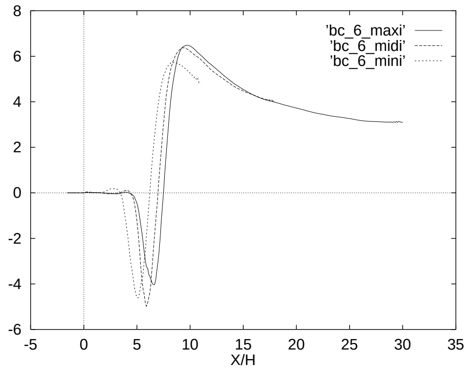

Figure 4: u_τ comparison for $L = 11H$, $17H$, $28H$ with the standard bc (6)

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 (7) presented in figure 3 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 (7) is the same as in the case of the standard condition (6).

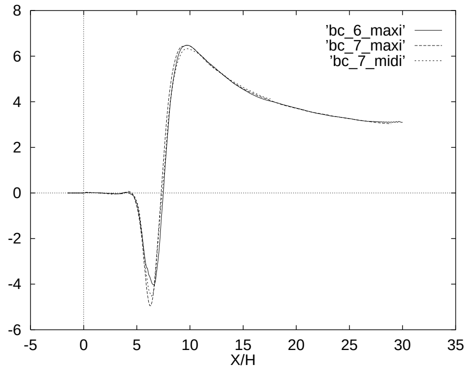

Figure 5: u_τ comparison for $L = 11H$, $17H$, $28H$ standard bc (6) and natural bc (7)

4. Results of the LES

The comparison of the DNS of the neutral bfs flow without a manipulation ($A = 0$) to the controlled cases with a fixed frequency of $f = 50\,Hz$ and a Reynolds number of 2970 for an amplitude of $A = 0.01\,u_{inflow}$ gives a decrease of the reattachment length X_r of more than 30%. This agrees with the experimental result of A. Huppertz (1995).
Figure 6 shows the LES-DNS comparisons of the graphs of the wall shear stresses u_τ for the control case. We get a very good agreement between the experiment ($X_r = 6.4\,H$) and the numerical simulation ($X_r = 6.48\,H$).

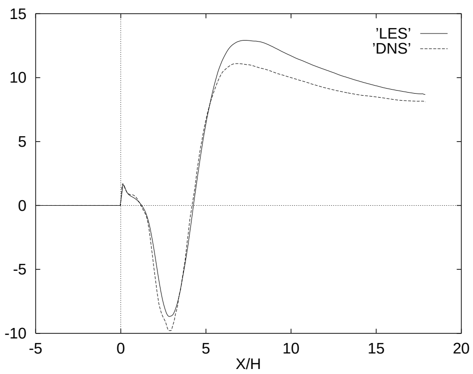

Figure 6: u_τ, DNS and LES, $A = 0.01u_{inflow}$

The results shown in figures 7 - 18 we obtained with the outlet boundary conditon (6). The markers in the figures represent the experimental data of Huppertz & Janke (1997). For the LES results we use continous lines, for the DNS results dotted lines.

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